JAN 18 '43

Volume 12 DECEMBER, 1942 INDEXED Number 3

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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The *Journal of Sedimentary Petrology* is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in April, August and December.

The subscription price of the *Journal of Sedimentary Petrology* is $3.00 per year prepaid to addresses in the United States.

Single numbers, $1.50 each.

Postage is charged extra for all other countries: 40 cents on annual subscriptions (total $3.40).

The *Journal* will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the *Journal*, subscriptions, rates, memberships, change of address, advertising and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P.O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 3, PP. 99–110,
FIG. 1, DECEMBER, 1942

THE RATE OF DEPOSITION OF SEDIMENTS: A MAJOR FACTOR CONNECTED WITH ALTERATION OF SEDIMENTS AFTER DEPOSITION*

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ABSTRACT

. Rates of deposition of marine sediments are shown to be highly variable. Slow rates of deposition permit long contact of the sediments with sea water and with bottom dwelling organisms. These organisms rather thoroughly search the slowly deposited sediments for contained nutrient matter, macerate them in their chewing organisms, pass them through their digestive systems, and more or less completely destroy all shells and tests. The sediments ultimately become excremental in character in which perfect shells may be expected to be uncommon. The more abundant the organisms on bottoms of slow deposition, the less are the possibilities of the sediments containing other than fragments of shells. Slow deposition also leads to the formation of certain minerals of which glauconite is an example. Rapid deposition, on the other hand, swiftly removes sediments from contact with the sea water and the destructive work of bottom dwelling organisms. These sediments contain little excremental matter; they may contain many perfect shells and most of any organic matter deposited with them.

INTRODUCTION

With the exception of alterations which depend upon the characters of the sediments, it is believed that the most important factor concerned with alteration of sediments after deposition is the rate of deposition. Rapid rates of deposition either preclude, or at least greatly limit alteration of already deposited sediments. Slow rates make possible many changes which take place after deposition. In the discussion which follows, standing water conditions are implied and the conditions, unless otherwise noted, are marine.

Sediments range in character from gravels through sands, silts, and clays to limy materials. It is considered unlikely that many changes take place in gravels after deposition except as the changes are produced by great heat or pressure or both. Such is also the case for most sands, but if the sands contain nutrient organic matter, it may be expected that they will be eaten by macroorganisms and subjected to some changes in their digestive tracts. Silts and clays, or the muds, may be expected to undergo changes both because of the fineness of the composing particles and also because of the likelihood of their containing much organic matter which renders them desirable to organisms for food. Lime sediments under almost any condition result to a greater or less degree from the activities of organisms and thus may be expected to contain nutrient organic matter and to be sought by organisms for food.

RATES OF DEPOSITION

Rates of deposition may be considered on the bases of what actually is known and what are the consequences of rates ranging from negative to very high.

From what is known of the rates of deposition, it is obvious that these are extremely variable. Rates depend on the quantities of sediments supplied, the spreading abilities of the transporting agents in the body of water in which deposition takes place, and the relations of the sites of deposition to the profiles of equilibrium or the base levels of deposition.

Rates of supply of sediments are as variable as the characters of the areas from which the supplies are derived. The

* This paper and the three which follow were presented as parts of a symposium at the Denver Meeting of the Society of Economic Paleontologists and Mineralogists, April, 1942.

characters of these areas depend upon topography or relief, the extent of development of vegetation, the activities of the animals on the land and in the soils, the thickness of the soil cover, the nature of the underlying rocks on which the surface is built, the elevation above sea level, the distances of the high places from the places of deposition, the nature of the climate, rainfall quantity and intensity, the snowfall particularly with respect to rate of melting, relation of rainfall to preceding weather whether such has encouraged a lush growth of vegetation or has been so dry as to discourage growth, and within the historical period upon the cultivation and pasturage of land by man. A high area close to the sea will supply more and coarser sediments to the sites of deposition, other things being equal, than an area of equal elevation above sea level far away. More sediments will be supplied by a land with a poor plant cover than one with a lush plant cover, more by a land with much relief than a land with little relief, and more by cultivated lands than those which are not cultivated. Each of the factors is a variable, hence the quantities supplied cannot fail to be of wide range.

The spreading effects of the transporting agents—the waves and currents—vary with the body of water into which the sediments are transported. Where waves and currents are strong, a great volume of sediments may be spread as a thin sheet over a vast area, and as a thick deposit over a small area if the waves and currents are weak. The Amazon with the strong currents which it brings to the Atlantic is stated to spread its sediments outward from its entry into the sea for a distance of around 300 miles, whereas the sediments brought to the Gulf of Mexico by the Mississippi River are not carried nearly so far to the extent that the transportation is indicated by the surface waters. An important current in spreading sediments outward from shores of standing bodies of water is produced by differences of density of waters rendered turbid because of sediments in suspension and other adjacent waters which are not turbid. There is thus a turbidity gradient from the turbid to the clear water and this leads to movement from the former to the latter. A shore violently stirred by the breaking of waves becomes exceedingly turbid if the bottom is composed of sediments of silt and clay size. The turbidity gradient is then from the shallow waters about the shores to the deeper waters outward and a density current moves outward which spreads sediments more or less widely over the adjacent deeper bottoms.

After an area of deposition has attained the base level of deposition, either temporary or permanent, it is not possible for permanent deposits to be made on that area. Temporary deposits may be made during times of low competency and capacity of the transporting agents, but these may be expected to be removed when competency and capacity of transporting agents are increased. Under average conditions, sediments are bypassed over such areas.

Known or Estimated Rates of Deposition.—Estimates of rates of deposition have been made from time to time, but most of these are hardly more than guesses and have little or no support in either experiment or observation. In a few cases, actual rates of deposition have been determined. One may know how much sediment is supplied to a certain site of deposition, but this would serve no purpose if the extent of spreading of this sediment over the site were not known. One can easily learn what would be the rate of deposition if a known quantity of sediments was deposited in equal thickness over a given area, but such equal deposition probably has never been the case over bottoms beneath moderately shallow water and probably never will be the case. It may be assumed that each site of deposition has an average rate, but this can be no more than a summation of variations of rates in time and over the same area at any one time. It is known that these rates vary greatly. The deposit made during one month over one part of a site of deposition may be a mere frac-

tion of an inch, another area of the same site of deposition may be eroded, and still another area may receive an annual thickness of several feet. A place during one year may receive a certain thickness of sediment and during the following year the thickness may be several times that quantity. The Colorado River carried 91,348,000 tons of "silt" past Yuma, Arizona, in 1918, and 308,728,000 tons in 1905, the latter more than three times the former. These variations in supply are known to every student of recent sediments.

Johnston states that the Fraser River of British Columbia deposits as much as 20 feet of sediments in the Strait of Georgia in a single year and a thickness of three feet is known to have been deposited in a single day in places about the mouth of the Mississippi. Essentially nothing is known of the rates of deposition over shallow bottoms of the sea at those distances from the shore where the sites of deposition are beyond the immediate influence of the land, the source of most of the sediments. It is not known whether the average rate of deposition over such areas is a fraction of an inch per annum or some multiple of an inch. Likewise, nothing is known of local rates of deposition. If any part of the bottom of these shallow water sites of deposition has attained the base level of deposition, the rate of permanent deposition is zero and if any condition should develop to bring the bottom above that level, the rate would become negative and some of the sediments already deposited would be removed.

It is thought that the most stable and uniform rates of deposition are over the bottoms of the deep sea as the overlying waters seemingly should yield a more or less constant, although small, supply of sediments and the general conditions are such as to make possible maximum spreading of the sediments supplied. From this is should follow that the deposits of any year should be about as thick as those of any preceding or succeeding year.

After an evaluation of all the data in 1929, the writer obtained an average rate of deposition over the deep sea bottom of one foot in a little over 80,000 years. No claims were made respecting accuracy. Results were considered approximate. Kuenen, by another method of calculation a little later, obtained a rate of one foot in about 30,000 years and rather facetiously noted at the same time that the figure obtained by the writer was a "shrewd guess." Opinions may differ. Schott from study of the sediments obtained by the "Meteor" in 1925 to 1927 determined the rate to be one foot in 25,000 years. Bradley and others from studies of cores obtained in the North Atlantic by the Piggott core sampler found a rate of deposition over that part of the bottom of the deep sea of one foot in 20,000 years. As contributions to the bottom deposits of the North Atlantic have been made by icebergs since the Glacial Period, it is probable that accumulations of sediments over this part of the deep ocean bottom may be made somewhat more rapidly than elsewhere where such conditions do not exist. The estimates of rates vary within the range of one to four, and in every estimate of rate the annual increment of thickness is actually much thinner than a sheet of thin paper. Rates are necessarily small because of the smallness of the quantity of sediments supplied. These are derived from the atmosphere, from volcanic eruptions, from contributions of organic materials derived from substances in solution, and from fine materials floated outward from the shores. While the quantity floated per cubic foot of water is evidently small, the writer is of the opinion that the aggregate is very large and that much of the fine sediments, which are flocculated when stream waters meet those of the sea, do not settle, but because of the high content of water may float for a long time.

About the best that may be stated with respect to annual rates of deposition over the bottoms of marine waters adjacent to shores and below the base level of deposition is that essentially nothing is known other than that the annual rates

are subject to great variation with less than zero at one extreme and possibly several feet at the other, the former being due either to the bottoms being close to, at, or above the base levels of deposition, or to the smallness of the supply, and the latter to the bottoms being below those levels and subject to the entrance of large supplies of sediments. The deep bottoms of the sea are far below the base level of deposition and thus it is probable that a zero or negative rate never obtains although the annual increase in thickness is very small.

Estimates have been made from time to time of the comparative rates of deposition of the various kinds of sediments. It is thought that the ratios proposed are essentially without value if only lithology is considered. Ulrich estimated that a foot of limestone represents the same duration of time as 7 feet of mudstone or sandstone and Smith postulated that the deposition of a foot of limestone required as long a time as 10 feet of mudstone or sandstone. These figures hardly merit the respect of guesses. They were not based on any measurements of the rates of deposition of the respective sediments but represent ideas born in the minds of the proposers. It is thought that the figures are valueless and actually misleading. It is considered probable that in many instances a thin bed of sandstone may represent a longer time than many feet of limestone. It by no means follows that one 6-inch bed of sandstone represents the same approximate length of time as another 6-inch bed of sandstone with the same characters. One 6-inch bed deposited near the base level of deposition may represent thousands of years of accumulation, whereas another bed of the same thickness and character deposited below that level may represent the storm of a day. Furthermore, on many parts of the shallow bottoms the sediments are lime muds and sands and there seem to be no reasons why these may not be deposited as rapidly as muds and sands of other composition. The rates at which some oyster banks are known to accumulate are significant of how rapidly lime sediments may be deposited.

The writer has acquired some data respecting rates of deposition of lake sediments from studies of the sediments of lakes in the glaciated region of the upper Mississippi Valley. The figures seem to be accurate within fairly definite limits and the only unknown is the time since the departure of the ice from that region. This may be placed within a minimum and maximum number of years.

Lake Mendota, a hard water lake in the southern part of Wisconsin, in the vicinity of the city of Madison, has accumulated an approximate maximum thickness of 30 feet of calcareous sediments since the Ice Age, variously considered to have ended for that region some 25,000 to 50,000 years ago. This is the deposit over the middle of the lake where the bottom is far below the base level of deposition. In shallower water, however, the thickness is much less and the deposition of calcareous sediments approaches and certainly reaches zero over many, if not all parts of the shallow bottoms adjacent to the shores. As the sediments over the deeper parts of the lake contain about 70 per cent water, the 30 feet of wet sediments on lithification would reduce to about 9 feet of siliceous limestone, thus giving a rate of deposition of a foot of calcareous sediment in the range from about 2,750 to 5,500 years. This is a much slower rate of accumulation of calcareous sediments than is commonly assumed, which has been more or less generally placed at a foot in 1,000 years. The rate, however, is much greater than that of sands in the shallow waters of Lake Mendota and in some places a rate of deposition of sands of a foot in 25,000 to 50,000 years may be determined and yet the sands are cross-laminated and ripple marked and thus carry all the marks generally assumed as indicative of rapid deposition. The bottom of the sediments accumulated since the Ice Age is readily determined as they rest on deposits made by the ice or on the

underlying rocks. The differences between the deposits made since the ice retired and the materials of the base on which they rest are so distinctive that a mistake is hardly possible.

The rate of deposition of sediments in the deep parts of Lake Mendota is much greater than has taken place in the soft water lakes in the northern part of the state. The sediments which have accumulated in Grassy Lake, a woodland lake in northern Wisconsin, since the departure of the ice, if compacted, would not exceed 1.5 feet, or a rate of deposition of a foot in not less than 20,000 to 25,000 years. The rate of deposition in Crystal Lake, perhaps 10 miles to the east, would be about the same or slightly slower and in Little Long (Hiawatha) Lake it seems doubtful if the rate would exceed a foot in 25,000 years. After lithification these sediments would not be limestones but carbonaceous or bituminous shales. Devils Lake is situated in the southern part of the state in a region of quartzite terrane. A small stream has built a delta into a former deep part of this lake and the rate of deposition of the sediments in this delta may have been a foot in a couple of years.

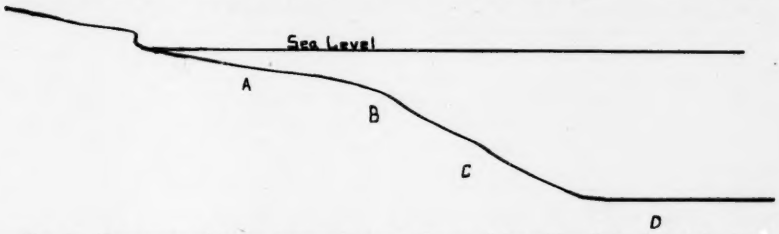

FIG. 1.—Four zones of the sea bottom in terms of rates of deposition. Zone A is at the depth of the base level of deposition and receives no permanent deposition of sediments. Zone B is below the base level of deposition but is affected by waves and currents of large competencies and capacities. The bottom is occasionally eroded. Zone C is below the depth of wave and current action and sediments once deposited are not later removed. Zone D is the bottom of the deep sea.

MARINE ENVIRONMENTS AND RATES OF DEPOSITION

From the point of view of rates of deposition, four environments of sea bottoms may be differentiated, of which each grades into those adjacent. The differentiation is based on the relations of the bottoms to base levels of deposition, rates of supply of sediments, and capacities and competencies of the transporting and distributing agencies. Base levels of deposition are related to position of sea level with respect to the bottom of the basin of deposition. The four environments are shown in the diagram of figure 1.

Zone A is at, or near, the depth of the base level of deposition. This may be a permanent level because of permanency of position of sea level, or a rising or sinking level because of rising or sinking of that level. Permanent or falling sea level permits no permanent deposits. Temporary deposits may be made, but ultimately all of these may be expected to be removed and carried to zones of deeper waters. Rise of sea level and thus rise of the base level of deposition permits deposition of a thickness of deposit more or less commensurate with the extent of rise of sea level. Rates of rise of sea level may be generally assumed to be low and thus most sediments deposited in Zone A under this condition may be expected to be subjected to bottom conditions for a long time. Supplies brought to such bottoms may at times exceed the disposition abilities of the waves and currents and temporary deposits may be made, but as supplies decrease, as may reasonably be expected, parts of these deposits are quite certain to be removed. Many minor to large disconformities and

discontinuities of record are thus made. The layers which are made and persist may be expected to contain a condensed representation of the faunas of a long time, thus making the condensation layers of Heim. On the other hand, although an immense duration of time may be represented by a small thickness of sediments, the faunal record may be expected to be more or less incomplete and it may be entirely absent in some parts because of destruction produced by scavenger organisms.

Zone B is below the depth of the base level of deposition. Rates of deposition in this zone are determined by rates of supply and capacities and competencies of the distributing and transporting agencies. Excessive competencies and capacities at times may lead to some removal of previously deposited sediments, thus leading to breaks in the record and disconformities. These become fewer with depth. If rates of supply are great and distribution is poor, parts of the bottom may be built to the depth of the base level of deposition and thus acquire the characteristics of Zone A. If spreading is excellent, deposits are much thinner, deposition is slower and exposure to bottom conditions endures for a longer time.

Zone C is assumed to lie below the depth of the wave and current action and to receive deposits which are permanent. Rates depend on quantities of sediments supplied, and degree of excellence of spreading of sediments. There are not likely to be discontinuities, but minor to large variations in thickness may be expected in the deposits which are made from year to year. Dependent on the extent of scavenger action, a complete faunal record may or may not be made in the deposits. If scavenger action is extensive, the faunal record may be very incomplete.

Zone D represents the bottom of the deep sea. Rates of deposition are low because of smallness of supply and excellent spreading by the distributing and transporting agents. Zone A would become zone B if sea level should rise to a sufficient degree or the area of zone A should sink; zone B would become zone C for the same reasons. The upper part of zone C may become zone B if sea level should fall sufficiently or the area of zone C should rise; zone B under the same conditions might acquire the characteristics of zone A. The lower part of zone C is not greatly different from zone D. Accumulation of sediments and rises and falls of sea level thus make possible the superposition of the deposits of the different zones. Large supplies of sediments and a sinking geosynclinal crust beneath zones B to C would permit large and thick accumulations over the bottoms of these zones with maintenance of a more or less constant depth of water.

The depth of zone A and the depth of its change into zone B vary with different bodies of water. The depths are controlled by the strengths of the waves and currents and these, in turn, are determined by shore topography, shore line configuration, and strength and fetch of winds. Depths are greater in large than in small bodies of water and on bottoms marginal to the open ocean than on the bottoms of epeiric or interior seas. Maximum depths in marginal seas, in general, are in the range of 200 to 300 feet. Widths of bottoms of zones A and B vary greatly. On some coasts these zones are narrow; on others wide. Widths are great in interior or epeiric seas and in such waters zones C and D may not exist.

IMPORTANCE OF RATE OF DEPOSITION ON CHANGES ON SEDIMENTS AFTER DEPOSITION

If sediments are rapidly deposited and thus overlie sediments that are rapidly buried, the latter are protected against the influences of processes operating on the bottom and from the work of bottom organisms. Slow deposition of sediments permits all of these things to take place.

Preservation of Organic Remains.—Sedimentary materials on the bottoms of water bodies and, in particular, the sediments on the bottom of the sea are searched by scavenger organisms for food if the conditions on the bottom do not

preclude their being present. Shells are broken and ground to small fragments through their work and under conditions of slow deposition nearly every substance of organic origin and all associated materials may be expected to be riddled or macerated by boring and chewing organisms, or crushed, ground, and dissolved in the digestive tracts of scavenger organisms. The organic materials which escape complete destruction are fragments and any fossil record that may be preserved can hardly be one of many complete shells. Bottom conditions may be the most favorable throughout the entire time of slow deposition for the bottom dwelling organism, but the more numerous the herbivorous forms, the more numerous are also the predaceous forms which feed upon them, and also the more numerous the scavenger organisms which feed upon the dead remains of herbivores, predators, and scavengers. Under congenial conditions the relations are extremely excellently balanced with the numbers of each kind adjusted to the numbers of the other kinds and thus there is a lush abundance of organisms on the bottom. This is a completely balanced association. The net result of these conditions may be expected to be that of complete destruction of the skeletal parts of all organisms and all nutrient matter so that nothing remains but fragments of which most if not all have made at least one passage through the digestive tracts of scavengers. This is perhaps the most significant consequence of slow deposition. *It seems a paradox that the more congenial the conditions on the sea bottom for bottom dwelling forms and the more numerous the colonization by organisms, the less likelihood is there of many fossils in the sediments which finally attain entombment. In other words, an abundant bottom population under conditions of slow deposition produces deposits with few complete shells and more or less complete elimination of all nutrient matter. Accumulation of organic materials is not possible under such conditions.*

The two places of slow deposition are not alike; the one in zone A and upper part of zone B and at or near the base level of deposition is within the influence of waves and currents, the other in the lower part of zone B to zone D is at depths below that influence. There is more or less constant agitation and aeration of the waters in the one place, and limited agitation and perhaps also limited aeration in the other. There are also differences of depth and hence of light and probably temperature. These factors certainly produce differences in the biologic environment and consequently in the biological associations. Thus, while the rates of deposition may be essentially the same, the characters and kinds of organisms may be expected to be different. The sediments may also be expected to be different. Those made beneath the agitated and aerated waters are certainly influenced by the capacities and competencies of the waters and these lead to removal of the fine sediments, whereas in the deeper waters competency and capacity to remove sediments are not present and everything which is deposited remains. Thus, the sediments in the shallow waters average coarser than those of the deeper waters. The differences in sediments and the sedimentary environmental conditions will also have influence on the bottom dwelling forms and lead to differences in the associations. In other words, rates of deposition over two areas of a sea bottom may be the same, but both sediments and contained shells may be very different.

Rapid deposition of sandy and muddy sediments creates difficulties for bottom dwelling forms. They daily face the hazard of burial beneath sediments. This offers difficulties for the vagrant benthos but they may manage to keep on top of the sediments as these are deposited and they may unearth themselves if temporarily buried, but burial means death to the sedentary benthos, and at the same time elimination of predators which are dependent upon the sedentary benthos for food and also to any scavengers which possibly may have been limited in their food to any of animals and plants destroyed or eliminated. It should be obvi-

ous that the association of organisms buried in the sediments under these conditions would be likely to be different from those entombed in sediments slowly deposited in case the shell materials escaped destruction. Furthermore, the association of fossil shells would not be likely to be a balanced one. Under the conditions of rapid deposition, sedentary benthos would not be likely to be present except at the base of a column of sediments which indicates the beginning of rapid deposition. Remains of organisms would be present throughout to which the conditions of rapid deposition were not a menace. Their remains to the extent preservable would be likely to be quickly buried after death and would have excellent possibilities of escaping destruction by scavenger organisms. The sedimentary rocks resulting from these postulated conditions may be abundantly fossiliferous, but the remains, except at the base, would be largely those of organisms which could dig themselves out if buried. Such may have been the conditions during the times of deposition of some of the Ordovician shales of the Cincinnati region which contain an abundance of trilobites and some pelecypods believed to be mud loving, but a scarcity of other forms. Limestones interstratified with the shales contain an abundance of shells on their surfaces which are clearly those of sedentary benthos. The interior parts of many of the beds of limestones are composed of fragments of shells, the result of slow deposition.

Some bottoms may be subject to conditions of rapid deposition alternating with slow deposition. Conditions of this character could exist beyond bottoms near the base level of deposition and shoreward and from the deep bottoms of slow deposition, particularly beyond the thick deposits about the mouths of rivers in the latter case. The areas shoreward from the places of slow deposition—seaward from the areas of rapid deposition (lower part of zone B and upper part of zone C of fig. 1)—would probably be those where these alternating conditions would most commonly prevail as the bottoms over the other areas nearer bottoms at the base level of deposition (upper part of zone B of fig. 1) would be places of interrupted and gradually increasing rapid deposition with depth. Under the conditions of variable deposition, there would be times of slow deposition when sedentary benthos together with their accompanying predators and scavengers would become established in association with each other. The consequences of slow deposition, already considered, would then prevail. This would later be followed by a time of rapid deposition produced by a large supply beyond the distribution ability of the waves and currents at the place. The rapid deposition would bury all sedentary benthos at the bottom of the deposit and probably many of the vagrant benthos to depths where they could not unearth themselves. The results would be death and the burial would protect the shells from destruction by bottom dwelling scavengers. Long continuation of rapid deposition would produce deposits containing largely the shells of vagrant benthos. Any part of a geologic section made by these conditions would have some beds replete with fossils with many in the positions where they lived, whereas other layers resulting from slow deposition would be composed of fragmentary shells and more or less small fragments of shells. The greatest abundance of shells of sedentary benthos would be about the bases of the layers of rapid deposition, shells in the higher parts of such layers would be less abundant and composed dominantly of vagrant benthos. Such is thought to have been the condition on Anticosti in the Ordovician and Silurian, on Gotland in the Silurian, and about Cincinnati during the Ordovician, where the limestones have the fossils in the interiors of the beds more or less fragmentary and represent the times of slow deposition and the separating beds of shale with excellently preserved fossils represent the times of rapid deposition. Fossils are commonly most numerous at the bases of the beds

of shale. The bottoms during the times of rapid deposition need not at any time have had a lush association of animals, but the excellent conditions of preservation would lead to an abundance of fossils when compared to the numbers of good shells in the layers of slow deposition.

The organic associations under the conditions of slow deposition, rapid deposition, and alternately slow and rapid deposition may have many species in common, but the associations would be likely to be different. Vagrant benthos would be likely to dominate in the sediments deposited under the conditions of rapid deposition; under the conditions of slow deposition only extremely resistant shells might be expected to be present in good shape.

Consequences of Activities of Mud-eating Organisms.—Slow and rapid deposition has other consequences related to the organisms which dwell on the bottoms where the respective conditions prevail. The animals which eat the sediments for the contained food transform the sediments swallowed to faecal pellets or some other form of excreta. As shown by A. B. Moore and others, these are very abundant in some marine deposits. Buchanan over fifty years ago stated it as his opinion that "the principal agent in the comminution of the mineral matter found at the bottom of both the deep and the shallow seas and oceans is the ground fauna of the sea, which depends for its subsistence on the organic matter which it can extract from the mud" and "the organic matter forming the bottom of the sea is continually passed and repassed through the bodies of the numerous tribes of animals which demonstrably subsist on the mud and its contents" and whose excretory products ultimately become the sediments finally entombed. Most sedimentationists and very few stratigraphers have taken this factor into consideration either with respect to the constitution of the sediments or the preservation of organic matter. If deposition is slow, the bottom sediments may be expected to be eaten many times and thus all the shells transformed into excretory products *with dimensions of all detrital and shell particles reduced.* Eating of bottom sediments is not likely to be extensive under conditions of rapid deposition. The sediments finally deposited under these two conditions would certainly be different, the one largely composed of materials which had passed one or more times through digestive tracts, the other of particles which had not been subjected to these conditions.

Work of Microorganisms.—Bacteria and other microorganisms seem to confine most of their activities to the upper one to two feet of a column of sediments. Under conditions of slow deposition, the upper one to two feet will be intensively affected by microorganic activity for a long time and all organic materials may be expected to be eliminated, whereas under conditions of rapid deposition the microorganic activity is exercised for only a very short time and the consequent changes will be limited. Organic matter is thus preserved and becomes a permanent part of the sediments.

Connected with the destruction of organic matter is the character of the water. This may prevent the presence of organisms, but also favor accumulation of organic sediments. Bottoms of poor circulation are deficient in oxygen and ultimately the waters become toxic, bottom organisms are eliminated, organic matter of planktonic and nectonic origins is not eaten, and hence accumulates. The waters of epeiric seas unders some conditions become highly saline and few organisms can exist. Accumulation of organic remains must necessarily be small. The waters about the mouths of streams become freshened by large inflow, all kinds of organisms are killed and any remains on the bottom at the same time are rapidly buried beneath inorganic sediments. Essentially everything of organic origin on such bottoms becomes part of the sediments as microscopic scavengers are also killed. Epeiric seas may also have salinity decreased by inflow of fresh water, as is the case in the Baltic Sea, and such seas, if shallow, may have

marked changes in salinity over a very short time. Such changes would be likely to decimate the aquatic life just as great rains at times have so changed the salinity about coral reefs that great destruction of the corals and associated organisms was brought about. Such decreases in salinity would be indicated in the geologic column by horizons filled with large numbers of fossils succeeded by horizons essentially barren of fossils. This idea of essentially fresh waters in epeiric seas seems to have received scant consideration, but if seas can become highly saline, they can also become fresh.

RELATIONS OF RATES OF DEPOSITION TO PRODUCTION OF NEW SUBSTANCES

It is known that several kinds of rocks and minerals are produced on sea bottoms by reason of the conditions of slow deposition and that they do not form under conditions of rapid deposition of muddy and sandy sediments. Slow deposition permits long contact of the bottom sediments with the substances in solution in the sea water. Slow deposition also permits pure deposits of some sediments which under conditions of rapid deposition would be disseminated throughout other sediments. Among the rocks produced are the limestones, flints (cherts) and some deposits of hematite, and limonite, and manganese oxides. If the deposition of muddy and sandy sediments is rapid it should be obvious that deposition of calcium and magnesium carbonates to make limestone in the form of beds is not possible. Carbonates will no doubt be deposited to a greater or less extent, but they will be mingled with sandy and muddy sediments and thus make no independent unit. It is thought that most of the silica transported to the sea in the waters of streams is in colloidal suspension. If the same waters carry muddy and sandy sediments in quantity, these sediments will be deposited together and thus the silica will be disseminated more or less throughout the deposits which are made. If there is limited transportation of muddy and sandy sediments it will be possible for the silica to become concentrated and to form units of flint or chert. The writer is of the opinion that the deposition of silica in the form of flint and chert due to silica of terrigenous origin takes place largely where the fresh waters of streams mingle with the salt waters of the sea and thus over the areas where the muddy and sandy sediments are normally deposited in the sea if they are brought thereto by streams. Silica makes deposits of flint and chert where there is little deposition of clastic sediments.

Moore and Maynard have shown that stream waters carry silicon dioxide and ferric oxide in colloidal suspension and when stream waters enter bodies of water containing electrolytes capable of flocculating these substances, the iron oxide is flocculated first, followed later by silica. Manganese oxides are carried in the same way. The iron and manganese oxides would be deposited on bottoms capable of retaining sediments at places nearest the shores, or places of entrance of stream water, whereas the silica would be deposited outward therefrom. If the deposition took place in still waters, the iron and manganese would be at the base and the silica would be above. If the same waters transported muddy and sandy sediments, these various substances would be mingled with the clastic sediments and thus make no independent deposits. If the clastic sediments were wanting or few, each of the substances could make an independent unit.

It now seems generally agreed that petroleum and allied substances are derived from organic matter. Under conditions of slow deposition, or if the bottom conditions did not preclude its being done, the bottom deposits are explored again and again for food by bottom dwelling organisms and after the possibilities for extraction of nutrient matter have been exhausted by these organisms, microorganisms continue the elimination of organic matter until the sediments are buried below the depth of their activities. The microorganisms do

not begin where the macroorganisms leave off, but are active from the first appearance of organic matter. Under favorable conditions of slow deposition nothing which might serve for food remains. Petroleum could not possibly have originated on aerated bottoms under conditions of slow deposition except as some of the products of the microorganic activity were not edible. Neither could it originate under conditions of extremely rapid deposition as these conditions do not favor and generally do not permit colonization of the bottom by organisms.

It would thus seem that the petroleum must have originated under conditions of moderately rapid deposition, alternate slow and rapid deposition, or under conditions where the bottoms were such that bottom dwelling forms could not live. Cunningham-Craig long urged that the materials in which the organic matter was entombed which resulted in petroleum were largely accumulated in the offshore deposits of rivers; that is, the submerged parts of deltas as these are places of protective burial of organic matter because of the rapid deposition. A favorable position would be a subsiding bottom which would permit continuance for a long time of the conditions as found in the lower part of Zone B and upper part of Zone C of figure 1, that is, in a geosyncline receiving large supplies of sediments. Places uninhabitable for bottom organisms are places of poor circulation like the bays with raised thresholds of Strøm, the "barred basins" of Woolnough, the "halistas" of Walther, and the "dead grounds" of Johnstone. These would be likely to be places of slow deposition but the organic matter would not be eaten because the conditions on the bottom preclude the presence of bottom dwelling forms.

Some authigenic minerals found in sediments seem to require slow deposition for their formation. Among these are glauconite, phosphate minerals, and the calcium aluminum silicate, phillipsite. There are others. It is generally agreed that slow deposition is necessary for the formation of glauconite whether the mineral results from the alteration of biotite as postulated by Galliher, develops directly from substances in the sediments and in the sea water, or represents the alteration of faecal pellets as suggested by Takahashi and Yagi. It seems quite certain that the mineral does not develop under conditions of rapid deposition. Hadding states that very slow to negative deposition is required.

It does not seem likely that the sedimentary phosphates develop as pure deposits during the times of rapid deposition except under very rare conditions, in spite of the fact that in many cases they are interbedded with clastic sediments. Phillipsite is a common constituent of the deposits of the deep bottoms of the sea and it does not seem to have been reported in the deposits of rapid deposition. It is thought that its formation requires long contact with sea water.

SUMMARY OF RATES OF DEPOSITION IN THE SEA

1. Slow deposition on bottoms near the base level of deposition leads to many disconformities and discontinuities of record.

2. Slow deposition at the depths below the base level of deposition and beyond the areas of rapid deposition yields a complete section without disconformities or discontinuities.

3. Slow deposition under genial biologic conditions may be expected to have more or less lush animal associations, but more or less complete destruction of shell materials and elimination of all nutrient matter and thus yield sediments with few well preserved shells, but much fragmentary shell materials and more or less free from carbonaceous or bituminous materials.

4. Slow deposition on bottoms near the base level of deposition but with rising sea level may be expected to produce sections with few to many discontinuities (dependent on the rate of rise of sea

level) and with the fossil remains in a more or less fragmentary condition.

5. Rapid accumulation of sediments may be expected to produce sections containing more or less complete shells which are largely those of vagrant benthos except at the base where there may be numerous shells of sedentary benthos.

6. Alternately slow and rapid deposition may be expected to produce layers largely composed of fragmentary shells alternating with layers containing excellently preserved shells with numerous sedentary benthos concentrated at the base of the rapidly deposited layers.

7. Limestone and flint (chert) indicate conditions of limited and slow deposition of muddy and sandy sediments.

8. The organic materials from which petroleum and allied substances were derived are deposited either under conditions of moderately rapid deposition, conditions of alternately slow and rapid deposition, or under conditions which preclude activities of scavenger organisms on and in the sediments after they were deposited. Conditions for rapid deposition or alternately slow and rapid deposition seem most favorable in geosynclines receiving large supplies of sediments and providing long continuances of shallow bottoms below the base level of deposition. Subsidence of the geosyncline should keep pace with accumulation.

9. Slow deposition permits formation of such substances as glauconite, phosphate minerals, and phillipsite.

10. Slow deposition may favor lush growth of bottom dwelling organisms but scavenger action will also then be lush with a consequent destruction and perhaps total elimination of shell or other skeletal matter.

11. Rapid deposition leads to early entombment, hence protection and preservation of shells.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 3, PP. 111–117,
TABLE 1, DECEMBER, 1942

PHYSICAL AND CHEMICAL CHANGES IN SEDIMENTS AFTER DEPOSITION*

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ABSTRACT

This paper discusses changes which occur in sediments between deposition and final lithification, under temperatures and pressures associated with near-surface conditions in the lithosphere. Among such changes are compaction, cementation, recrystallization, replacement, differential solution, and the development of authigenic minerals. The result of these changes is discussed in terms of sediment properties—composition, texture, and structure—with emphasis on textural changes. Problems of reconstructing original conditions of sedimentation in the light of these changes are also pointed out.

INTRODUCTION

Most sedimentary studies are made on recent deposits in which post-depositional changes are negligible, or on ancient sediments already thoroughly lithified. The "half-world" between these extremes—the domain of diagenesis—has not yielded readily to systematic study, although its importance has long been recognized. Growing emphasis on environmental aspects of sedimentation, especially as they bear on petroleum exploration, has awakened new interest in the subject. Modern exploration demands accurate reconstruction of original conditions of deposition, and this requires more exact knowledge of post-depositional changes.

There is no universal agreement on the definition of diagenesis. The writer follows Twenhofel (1939, p. 254) in this paper:

> Diagenesis includes all modifications that sediments undergo between deposition and lithification under conditions of pressure and temperature that are normal to the surface or outer part of the crust, and in addition, those changes that take place after lithification under the same conditions of temperature and pressure, which are not katamorphic in character so that the effect is delithification.

This definition eliminates regional and contact metamorphism on the one hand, and weathering processes on the other. Changes after lithification are included because diagenesis is a function of time; the greater part of a given change may occur soon after deposition, but some change takes place indefinitely at a decreasing rate. Physical compaction is an example, rapid at first and diminishing indefinitely thereafter.

This paper is one of several in a symposium. Its purpose is to review briefly the physical and chemical changes which occur during diagenesis, whether the changes be organic or inorganic. Emphasis is placed on changes in particular characteristics of sediments to indicate the degree to which selective processes may operate during diagenesis.

THE RAW MATERIAL OF DIAGENESIS

The raw material of diagenesis is the freshly deposited sediment at the interface between previous layers of sediment and the depositional environment. Diagenetic processes initiated while a given bed occupies this interface are continued or modified as the bed is buried beneath later sediments. During burial, pressure and temperature rise, and new changes may be initiated by the new conditions.

* Paper presented at the 1942 meeting of the S.E.P.M. and A.A.P.G., Denver, Colorado.

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The properties of freshly deposited material are controlled partly by conditions in the depositional environment. Variations in particle size, shape, and density of clastic particles are functions of the velocity and turbulence conditions in the medium. Similar relations hold between sediment and environment for non-clastics, but the control may be more chemical than physical.

Recent marine sediments have been studied in considerable detail by many workers; Trask especially (1932, 1939) describes a variety of modern marine deposits. From these and other sources it appears that freshly deposited sand contains about 45 per cent water; silt has from 50 to 65 per cent; and mud (clay) has from 80 to 90 per cent. Colloids (under 1 micron) have about 98 per cent water at the time of deposition. Water content under saturated conditions is a measure of porosity, so that this property also varies among fine and coarse sediments.

Particle size and organic content are related in sediments. Trask showed that the organic content of clay is twice that of silt, and four times that of fine sand. This indicates an exponential relationship between size and organic content, which was later demonstrated in the sediments of Barataria Bay (Krumbein and Caldwell, 1937). Although organic content varies widely in different environments, and is greater near shore than in the open sea, Trask's work indicates that in general sands may have from essentially none to about 0.6 per cent organic matter, whereas clays may have up to 8 or 10 per cent. The organic content of near-shore open sea sediments is about 2.5 per cent on the average. Calcareous marls, as near the Bahamas, may contain from 1 to 6 per cent organic matter.

In addition to initial differences in particle size, in water content, and in organic content, freshly deposited sediments differ in their mineralogical composition, and hence in their susceptibility to chemical change. This susceptibility ranges from the comparative stability of quartz sand to relatively active clays or finely divided non-clastics, with their large total surface areas. Chemical changes in part are a function of the size distribution of the sediment; base exchange, for example, may play a prominent role among very fine sediments, but it is generally negligible in coarser sediments.

THE ENVIRONMENT OF DIAGENESIS

The fluid associated with freshly deposited sediments may be air, fresh water or sea water. Associated water may contain dissolved solids and gases, themselves chemically active, or offering pH conditions and oxidation-reduction potentials (E_h) favorable for chemical reactions. Even a single medium, as sea water, may vary significantly in different environments. Fleming and Revelle (1939) discuss conditions in the open sea and in stagnant and non-stagnant basins. Marked differences may occur in dissolved oxygen, in temperature, in salinity, and in pH. Not only do such variations affect resulting chemical and physical changes, but they also control the degree to which biological organisms may participate in diagenesis. This aspect of the subject is discussed by Dapples and ZoBell in this symposium.

The active zone of marine diagenesis, in its initial stages at least, is the interface between sediment and environment. Water trapped with the sediment has the same composition as the original sea water, but differences appear as soon as this is sealed from free circulation by the accumulation of later material. The work of ZoBell (1939), Trask (1932), and others shows that there are systematic changes in the diagenetic environment downward from the interface.[1] Oxygen is practically depleted within a few centimeters below the interface. The oxidation-reduction

[1] The writer is indebted to Dr. C. ZoBell of the Scripps Institution of Oceanography for some of the material in this section. Dr. ZoBell develops the subject in detail in his own paper; the purpose here is to consider the diagenetic environment without regard to the specific agencies which may produce it.

potential also changes at the interface. Sea water has a small positive E_h value, indicating slightly oxidizing conditions. The value becomes negative downward, indicating a reducing environment. The greatest change occurs within the upper 5 to 10 cm. of deposit. At 25 to 50 cm. below the interface ZoBell found the E_h to be −0.4.

Both organic nitrogen and organic carbon decrease from the interface downward, but the nitrogen decreases more rapidly, so that marine cores typically show an increasing carbon-nitrogen ratio with depth. Data on the pH of the marine diagenetic environment are scarce. The pH of surface sea water varies from 8.1 to 8.4, and decreases slightly with depth. The pH of bottom muds at the interface is often about the same as that of the overlying water, from 7.8 to 8.1. ZoBell reports that in some cores the pH increases with depth to 8.9, whereas in others it decreases to as low as 7.2. No instances are known of definitely acid conditions (pH less than 7.0) in cores from the open sea.

It seems safe to conclude from the foregoing that the marine diagenetic environment is strongly reducing and moderately alkaline. The reducing tendency is an important factor in diagenesis. Debris carried to the site of deposition usually has passed through some stages of weathering before transportation, so that presumably part of its constituents are in their highest state of oxidation. Transfer of this material to a reducing environment, in company with dissolved salts, and subject to the action of new substances formed in the environment (hydrogen sulphide, carbon dioxide), undoubtedly sets the stage for mineralogical changes in the sediment. Iron and manganese, for example, may be reduced in part to lower stages of oxidation. Hendricks and Ross (1941) have shown that glauconite is formed only in environments with negative E_h values, and free from oxygen.

The marine diagenetic environment, while of greatest practical importance, is only one of a wide variety of diagenetic environments. A grouping of such environments, based on their pH, E_h, temperature, associated bacteria, dissolved substances, and so on, would yield information of considerable value to the further systematic study of the conditions under which post-depositional changes of one kind or another may occur.

CLASSIFICATION OF DIAGENETIC CHANGES

The preceding sections indicate that important factors in diagenesis are the particle size, water content, organic content, and mineralogical composition of the sediments on the one hand; and the temperature, pressure, and chemical condition of the environment on the other. As a result, a wide variety of diagenetic changes is possible, inasmuch as variations in the end-product may occur either with different sediments in the same environment, or with the same kind of sediment in different environments. The complexity of the general process is reflected by the fact that some 30 separate diagenetic processes have been described in the literature. These include the following:

Authigenesis	Intrastratal solution
Bleaching	Leaching
Carbonization	Lithification
Cementation	Oxidation
Compaction	Petrification
"Concretionary action"	Phosphatization
	Pyritization
Corrosion	Recrystallization
Dehydration	Reduction
Diffusion	Replacement
Dolomitization	Silicification
Enrichment	Solution
Glauconitization	Structural deformation
Hydration	
Induration	Subaqueous erosion

It is obvious from this list that authors differ in their definitions of "process." Some lists include products, such as stylolites and cone-in-cone, as processes. Some of the processes listed above are specific types of chemical reactions, as oxidation and reduction, whereas others

refer specifically to the kind of mineral produced (as glauconitization) regardless of the nature of the chemical change involved. Some of the processes are relatively self-contained, whereas others are combinations of several. Lithification, for example, may include cementation and other processes as factors.

A large field for research is open in the systematic study of diagenetic processes. This systematization may be accomplished in several ways. The processes may be classified according to the chemical reactions which are involved (reduction, oxidation, neutralization, hydrolysis, etc.); or they may be classified according to the specific environmental conditions under which they occur, as in the example cited for glauconite. A purely operational approach to a simplification of terminology may be made by considering the possible modifications of a single particle in a layer of freshly-deposited sediment, either clastic or non-clastic. The particle may be (1) moved into closer contact with its neighbors by pressure; (2) it may be surrounded by precipitated material; (3) it may be changed in size and form by recrystallization without changing its composition; (4) it may be changed in composition by replacement without changing size or form; (5) it may be wholly or partially dissolved; or (6) it may be changed in size, form, and composition by chemical alteration. These several possibilities may be expressed in terms of the previous list as follows:

1. Compaction
2. Cementation
3. Recrystallization
4. Replacement
5. Differential solution
6. Authigenesis

This simplified list is subject to some of the same criticisms as the longer list, in that the processes are neither independent nor mutually exclusive. However, most of the previous items may be classified under one or more of these six headings. The simplified set of processes are actually interrelated aspects of a complex system of phenomena, some of which may occur simultaneously. This complexity may be expressed analytically by assuming that the rate of change of any one process with respect to time is a function of itself, of the other five processes, and of environmental factors. Thus the segregation of individual diagenetic processes is difficult analytically, and this difficulty is reflected in any attempt to distinguish among them qualitatively.

1. Compaction.—Compaction of sediments is a reduction in their volume expressed as a percentage of the original voids present. The principal cause of compaction during diagenesis is the force exerted by the increasing overburden of later sediments. The magnitude of the effect is a function of the porosity and water content of the original sediment; of the size and shape of its particles; of the rate of deposition and thickness of the overburden; and of the factor of time. Athy (1930) showed that the porosity of shale is a negative exponential function of depth of burial. He found no definite trend for sandstone compaction, but some reduction of volume does occur in loose sand under pressure. Lime mud probably has a compaction history similar to shale until lithification is complete.

2. Cementation.—The deposition of minerals in the interstices of sediments is one of the commonest diagenetic changes. The cementing material may be derived from the rock itself or it may be brought in by solution. Cementation may occur concurrently with deposition, or may follow it with a time lapse. In some instances cementation is a function of simultaneous recrystallization.

3. Recrystallization.—Recrystallization is a general term applied to changes in crystalline texture caused by a growth of small crystals and fragments into an aggregate of coarser crystals. The process is more common among non-clastics than among clastic rocks. Depth of burial may be a factor, inasmuch as solubility at grain contacts is increased by pressure. However, recrystallization may occur essentially simultaneously with deposition. During recrystallization the smallest grains and crystals tend to disappear, and the larger particles increase in size.

4. Replacement.—Replacement is a process by which a new mineral may grow within and take the place of another mineral or mineral aggregate, without changing the external form. Among specific diagenetic effects which involve replacement are silicification, dolomitization, phosphatization, and pyritization.

5. Differential Solution.—Solution is perhaps the most common phenomenon of diagenesis. It is involved in cementation, recrystallization, and replacement. Despite the almost universal presence of solution effects, and the practical difficulty of separating it from other processes, it is believed that it should be described separately. Especially important here is the problem of intrastratal or differential solution, which has recently received attention from several writers (Bramlette, 1941; Pettijohn, 1941).

6. Authigenesis.—Authigenesis is defined as the occurrence of new minerals in a sediment during or after deposition, either by direct introduction or by the alteration of original constituents. As defined, the process includes aspects of cementation and replacement. Its inclusion as a diagenetic process is justified by the almost universal occurrence of mineral changes in sediments, regardless of the specific process which forms them. Some authigenic minerals are formed very shortly after deposition; others apparently form after deep burial and at higher temperatures.

EFFECTS OF DIAGENESIS ON SEDIMENT PROPERTIES

The petrographic study of any sediment includes a description of its composition, its textures, and its structures. During diagenesis each of these properties may change, and corrections must be applied in reconstructing original conditions of deposition from the observed properties. Among coarse clastics these corrections are often relatively minor, whereas among fine clastics and non-clastics the final rock may bear no close resemblance to the original deposit. Twenhofel for example (1937) describes a black, organically rich lake sediment (sludge) which changes by diagenesis to a light colored calcareous marl within a few feet of the surface of the deposit.

Among textural features which may change during diagenesis are particle size, shape, surface texture, and orientation. Mass properties as porosity and permeability are also usually changed. The following paragraphs describe some of the modifications which specific sediment properties may undergo.

1. Particle Size.—Particle size may be changed by cementation (secondary enlargement), by recrystallization; by solution; and by the introduction of authigenic minerals. Changes in particle size are most marked in fine grained clastics and non-clastics; in the latter the final size distribution may bear little resemblance to the original. Secondary enlargement and recrystallization may actually increase average particle size.

2. Shape (Sphericity) and Roundness.—Particle shape and roundness may be changed during diagenesis by solution, recrystallization, secondary enlargement, and authigenesis. Among non-clastics particle shape and roundness may have little diagnostic value as far as conditions of sedimentation are concerned, but marked shape changes may often be expected. Solution effects particularly are difficult to evaluate; sphericity, for example, may either increase or decrease during solution, depending upon physical conditions.

3. Surface Texture.—Solution, secondary enlargement, recrystallization, and other processes may affect surface textures of particles during diagenesis. Polish or gloss, for example, may be induced either by solution or by the deposition of thin films on the particles. The sensitivity of particle surfaces even to mild diagenetic effects suggests that a large field awaits quantitative study here.

4. Particle Orientation.—Very little is known about changes in particle orientation during diagenesis. Shifts in orientation may occur during compaction; if so, the effect is probably controlled by particle shape and water content. Particles may be completely re-oriented during recrystallization. Introduction of authigenic minerals may result in crystals arranged differently from the main depositional fabric. As with surface texture, much research remains to be done in this field.

5. *Porosity.*—Practically all diagenetic processes affect the porosity of sediments. Compaction, cementation, recrystallization, and solution may be particularly important. The final product may have either a larger or smaller porosity than the original; it is doubtful whether the observed porosity of consolidated sediments bears any simple relation to original porosity at the time of sedimentation.

6. *Permeability.*—The permeability of sediments is very sensitive to diagenetic change. It responds strongly to relatively minor changes in compaction, cementation, and recrystallization. As with porosity, it seems doubtful whether the observed permeability of indurated sediments bears any simple relation to original permeability. Among clastic sediments the reconstruction of original permeability must depend largely upon estimates of original particle size, degree of sorting, and other factors, as opposed to the degree of compaction and cementation introduced during diagenesis.

7. *Mineralogical Composition.*—Post-depositional changes in mineralogical composition have been studied in more detail than any other aspect of diagenesis. Some two dozen common authigenic minerals are known (Twenhofel, 1939, pp. 266–267), together with some information on their relative times of introduction. Less well understood are the physical and chemical conditions under which the minerals were introduced. The work of Hendricks and Ross on glauconite (1941), and of Grim (1939) and co-workers on clay minerals, furnish examples of progress in this direction. The interpretation of authigenic changes is well illustrated by the work of Smithson (1939).

8. *Color of Sediments.*—Sediment color may be completely changed during diagenesis. Reducing environments may change the red color of ferric iron to more neutral shades. If organic matter is removed during diagenesis, the color may lighten. The introduction of ferrous sulphide into sediments during early stages of diagenesis may darken them; subsequent recrystallization of this material to pyrite or marcasite may again lighten the color. Authigenesis may introduce a dominant color into the sediment, as the greenish tinge of some glauconitic sediments. Observed color of consolidated sediments may have little diagnostic value in terms of original conditions of sedimentation.

9. *Structures of Sediments.*—Original bedding in bottom muds may be altered or destroyed by organisms. This aspect of post-depositional change is discussed elsewhere in this symposium. Post-depositional slumping or sliding may give rise to contemporaneous deformation structures. Recrystallization may cause deformation of structure if the new materials have a larger volume than the original.

EVALUATION OF DIAGENETIC CHANGES

Although no rules apply universally in the interpretation of diagenetic changes, the writer has attempted to summarize the foregoing discussion in a table which suggests the relative magnitude of changes that may occur in sediments after deposition. This summary is given in Table 1, which lists the six diagenetic processes across the top, and some half dozen sediment properties on the left.

This table is offered as a rough guide for estimating the kinds of changes which may have occurred under given diagenetic conditions. For example, if the study of a limestone shows that recrystallization played a large part during diagenesis, the table indicates that practically every original property of the sediment may have changed. On the other hand, if an inorganic shale shows evidence mainly of compaction, the table suggests that some of its properties may be substantially the same as originally. Combinations of diagenetic processes afford some basis for estimating how seriously the properties of the rock may have been modified, thus giving a basis for applying necessary corrections in reconstructing the characteristics of the original sediment. In similar manner, the table may be useful in indicating which diagenetic processes may have occurred, on the basis of changes observed in the sedimentary rock.

CONCLUDING REMARKS

The complexity of diagenesis as a whole accounts in large part for the present

TABLE 1. *Relative Effects of Diagenesis on Sediment Properties**

Property	Compaction	Cementation	Recrystallization	Replacement	Differential solution	Authigenesis
Size	—	x	xxx	—	xx	xx
Shape and roundness	—	x	xx	—	xx	xx
Surface texture	—	x	xx	x	xxx	xx
Particle orientation	?	—	?	—	?	x
Mineral composition	—	xx	x	xxx	xx	xxx
Porosity	xx	xx	xx	x	xx	xx
Permeability	xxx	xxx	xx	x	xx	xx
Color	x	xx	x	x	—	xx

* Legend: x = small to moderate effect; xx = moderate to large effect; xxx = property most strongly affected by a given process; — means a negligible effect; and ? indicates an unknown effect.

cumbersome terminology and for the lack of systematic criteria for evaluating diagenetic changes. Needed research includes a more detailed study of the physical and chemical nature of the several diagenetic environments, as well as a study of the physical and chemical conditions under which specific diagenetic changes can occur. Measurable attributes of sediments deserve much more attention during diagenetic studies than has been accorded them. The absence of data on changes in particle shape, orientation, and surface textures illustrate the gaps in knowledge.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 3, PP. 118–126,
TABLES 1–6, DECEMBER, 1942

THE EFFECT OF MACRO-ORGANISMS UPON NEAR-SHORE MARINE SEDIMENTS*

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ABSTRACT

Macro-organisms which may directly affect marine sediments after their deposition are limited to benthonic forms which burrow for shelter or in search of food, and those which ingest sediments for the contained organic material. Changes which are produced by such organisms are: destruction of bedding, destruction of gradation of grain size, trituration and solution of rock masses and fragments, formation of tubes and burrows, addition of faecal debris, initiation of cementation, bleaching or coloration, and destruction of organic material. Since the degree of alteration is directly proportional to the number of benthonic organisms, the greatest changes must occur where the optimum dwelling conditions exist; hence, not in regions of stagnant water, nor where sedimentation is rapid.

Man's early interest in sea dwelling life as a source of food produced a fund of knowledge concerning its behavior long before his scientific curiosity was extended to include the field of geology. Therefore, the observation that organisms become entombed in sediments and are preserved as fossils was the normal outgrowth of an understanding of the habits of marine life. The seemingly mysterious occurrences of organisms preserved in stone furnished the stimulus to know more concerning the life which had lived in the past. This led to continued examination of sedimentary rocks, and the development of the present sciences of paleontology and stratigraphy. Paleontologists have been concerned with the examination of the preserved organic remains which at the time of their burial were dead or nearly so, and not with the sediments which served as a protective encasement for the buried organisms. The normal outgrowth of such an interest is that much is known concerning the identification and classification of life which was buried in past geological periods. But there exists only a superficial understanding concerning the effect of the organisms upon the sediments in, or upon, which they lived. All students of sediments have been impressed with the profusion of fossils to be found in certain strata. And, as their interests have been drawn toward marine biology, they, likewise, have been impressed with the tremendous quantity of benthonic life which crawls on, or burrows in, the sediments on the floor of the ocean. It is the effect of such organisms upon sediments already deposited to which the writer wishes to direct attention.

* Presented before the Society of Economic Paleontologists and Mineralogists, Denver, Colorado, April 1942.

DISTRIBUTION OF ORGANISMS

In many, but not all environments in which marine deposits accumulate benthonic life is abundant. Certain of these organisms burrow for shelter or food, or they may ingest the sediments in search of any contained organic material. Either of these two behaviors results in some alteration of the sediments already deposited. A list of such changes includes obliteration of stratification, destruction of gradation of grain size resulting from normal settling through an aqueous medium, trituration and solution of rock masses and fragments, formation of tubes and burrows, addition of faecal matter, initiation of cementation, bleaching of the sediments, and reduction of the amount of contained organic material.

On the basis of present meagre quanti-

tative information, there is reason to believe that the larger organisms which contribute to diagenetic changes are holothurians and worms, whereas, rock boring organisms and echinoderms are secondary in importance. Obviously, the degree to which any of the alterations already listed may take place is dependent upon the quantity of these organisms dwelling in any particular area and, hence, is in turn dependent upon the localities which possess the optimum living conditions. It is a well established fact that the majority of benthos live in waters less than 180 meters deep, yet shore dwelling annelids may range to depths of 1800 meters, and pelecypods, gastropods, and holothurians to depths of 4000 meters (Hesse, Allee, and Schmidt, 1937, pp. 151–152). Clarke (1907, pp. 66–67) describes the Synaptidae (holothurian) as having a bathymetric range from low water to 4200 meters. The great majority live in the neritic life zone (0–200 meters) and only a few species are found in waters deeper than 350 meters.

Apparently, the factor which chiefly limits distribution and population density of animals is food, but under certain conditions, oxygen concentration may be the control over the number of organisms present. Foul waters, that is, those low in oxygen content, may be caused by the decay of great swarms of dinoflagellates or by the presence of hydrogen sulphide. McClendon (1918) describes an instance in which the dinoflagellate *Gonyaulax polyedra* was so abundant that the water had a putrid odor and resulted in the death of some fish. Also, in some Scandinavian fjords, waters sufficiently rich in H_2S to destroy oysters may rise to within 4 feet of the surface (McClendon, 1918, p. 234). Other conditions are also important in controlling the zoning of benthonic life. For example, Kindle (1930, p. 11) reports a condition in The Wash where one-quarter mile from the low tide margin a zone of *Cardium edulis* is entirely supplanted by a marine worm *Branchiomima vesiculosum*, yet the worm is not found in the mid-area of the Cardium zone. Benthos may be particularly sensitive to changes in pH. MacGinitie (1935, p. 669) noted that when certain algae growing in a California estuary were exposed to the air during low tide, the pH of the surrounding water was increased greatly to as much as 9.8. Such a high degree of alkalinity resulted in the destruction of many organisms which ordinarily lived in great profusion in this zone. Despite such periodic destruction of life, such data as are available concerning the distribution of benthos, which have the most pronounced diagenetic effect upon sediments, indicate that they may be extremely abundant in certain localities (table 1).

All of the large organisms which help to produce alterations in sediments tend to avoid environments where the following conditions obtain:

(1) Regions of semi-locked basins, or those having a threshold floor, where circulation is poor.
(2) Areas of loose shifting sand.
(3) Waters through which mud is settling.
(4) Hard clay bottoms.
(5) Estuaries where the salinity may be low.

The preferred conditions are rocky bottoms for rock borers, those covered with well packed sand for holothurians, and mud bottoms containing much admixed sand for worms. Conversely, zones of heavy deposition such as deltas, muddy and stagnant waters, zones of fresh water influx which may kill the plants and cause an increase in the pH of the water, and even deep waters are the localities in which organisms will have a minimum effect upon sediments. Environments which approach the optimum conditions for bottom dwellers are the tidal flat, the near shore neritic zone, the coral lagoon, and the seaward borders of low lying islands. Hence, in such environments organisms should exert the greatest influence upon the accumulating deposits.

TABLE 1. *Distribution of Some Macro-Organisms Which Attack Sediments.*

Location	Authority	Organism	Distance from Low Tide Margin in Feet				
			0–124	200–324	400–484	526–624	700–874
1. Samoa	Mayer (1924a)	Holothurian individuals	277	298	305	46	7
2. Fringing reefs near Samoa	Mayer (1924b)	Holothurian individuals	average 8.6 per sq. ft. of reef flat				
3. Bermuda	Crozier (1918)	Holothurian individuals	average .02 per sq. ft. of reef flat				
4. Tahiti	Gardiner (1931)	Mollusk (*Lithophaga*)	average 100 per sq. ft. of reef flat				
5. English Channel Belgian Coast	Damas (1935)	Mollusk (*Cardium*)	average 91 per sq. ft. of reef flat				
6. North Sea Wilhelmshaven	Hantzschel (1939)	Mollusk (*Mytilus*)	millions of individuals on flat				
7. Channel Islands	Hesse et al. (1937)	Worm (*Turtellaria*)	maximum: 303,750 individuals per sq. ft.				
8. The Wash	Kindle (1930)	Worm (*Branchiomima*)	hundreds of tubes per sq. yd.				
9. Mouth of Elbe River	Dahl (Hesse et al. 1937)	Amphipod (*Bathyporeia*)	800 individuals in prism $1 \times 1 \times \frac{1}{4}$ meters				

DEBRIS INGESTED BY ORGANISMS

Holothurians and worms are extremely voracious, and their eating habits result in pronounced effects upon the ingested sediments. Mayer (1924a, p. 34) conducted experiments on the holothurians *Stichopus mobii* and *Holothuria mexicana* to determine the amount of solution of calcareous sand which occurs in passing through the bodies of these organisms. Large holothurians were observed to defecate from 72–94 g. of sand in 24 hours, and a specimen of *Holothuria mexicana* 24.5 cm. long dissolved 16 g. of calcareous sand in 25 days, a rate of 234 g. per year. Another holothurian over a 30-day period dissolved calcareous sand at the rate of 414 g. yearly. Mayer estimates that on the Aua reef flat at Samoa 290,000 individual holothurians each dissolving an average of 324 g. per year would destroy 104 tons of sand and lower the entire reef flat .2 mm. per year (table 2). Crozier (1918) has calculated that 4.2 kilograms of sediment is ingested by a single holothurian in a month, and in an area of 1.7 sq. miles on Harrington Sound, Bermuda, between 500–1000 tons of material pass through the bodies of holothurians in the same length of time. This is equivalent to 6–12 tons per year per acre of ocean floor in Harrington Sound. Elsewhere in the same locality extrapolation of Crozier's data indicates as much as 27 tons per acre per year are ingested by holothurians. Davison (1891) weighed the castings of *Arenicola* deposited on six small areas along the littoral of Holy Island off the coast of Northumberland. Extrapolation of the data obtained indicates that the tons of material deposited as castings per acre per year in each of these areas are 901; 3,146; 3,147; 449; 396; and 329. Assuming that such worms may be found to a depth of 2 feet, Davidson estimates that the entire sedimentary layer through which such worms burrow must pass through their bodies in the space of 22 months. Tables 3 and 4 are summaries of the existing data on the depth to which certain benthos burrow. Except for a few cases most of the organisms are found at a depth of less than one foot; hence, only the upper sedimentary layer is affected by their activities.

Gardiner, Mayer and others are of the opinion that in coral lagoons much fine

material resulting from trituration within the bodies of organisms is carried out by currents to the open ocean. This belief is supported in part by the results of mechanical analyses of coral lagoon sediments in a number of widely separated localities (table 5). An analysis of the data presented in table 5 indicates that in a number of coral lagoons, particularly in the Pacific Ocean, the sediments on the floor have a median diameter grain size of coarse sand or larger. Also, the cumulative size-distribution curves of such sediments are skewed in a negative-phi direction indicating that there is a wider distribution of coarse material than fine. In such instances much of the fine material has doubtless been removed by some agency. In other coral lagoon areas, particularly in the Atlantic Ocean, the median diameter grain size is of silt or very fine sand dimensions. The coarseness of the lagoon sediments of the Pacific appears to substantiate the suggestions of Mayer and Gardiner that much of the material passing through the bodies of organisms is ground to sufficiently fine dimensions to be eventually dissolved when inside the body of the organism, or such fine debris is carried into deep water by currents. The accumulation of fine debris in the cases of the Atlantic coral areas suggest the absence of currents of sufficient capacity to sweep particles of silt dimensions and smaller from the bottom.

TABLE 2. *Sediment Ingested by Benthonic Macro-Organisms.*

Location	Authority	Organism	Amount Ingested Per Individual
Florida	Mayer (1924b)	Holothurian	72–94 g. in 24 hours
Maldive Islands	Gardiner (1931)	Holothurian (average of 5)	19.4 g. in 24 hours
Maldive Islands	Gardiner (1931)	Holothurian (average of 5)	24.3 g. in 24 hours
Maldive Islands	Gardiner (1931)	Holothurian (average of 5)	19.8 g. in 24 hours
Maldive Islands	Gardiner (1931)	Holothurian (average of 5)	15.4 g. in 24 hours
Maldive Islands	Gardiner (1931)	Holothurian (average of 5)	4.5 g. in 24 hours
Bermuda	Crozier (1918)	Holothurian (average of 97)	77 g. in 24 hours
Bermuda	Crozier (1918)	Holothurian (average of 37)	175 g. in 24 hours
Bermuda	Crozier (1918)	Holothurian (average of 675)	20 g. in 24 hours
Bermuda	Crozier (1918)	Holothurian (average of 67)	43 g. in 24 hours
Bermuda	Crozier (1918)	Holothurian (average of 63)	79 g. in 24 hours
Maldive Islands	Gardiner (1931)	Worm (*Balanoglossus*)	225–280 g. in 24 hrs.
Naples	Shipley (1894)	Worm (*Sipunculus*)	16 g. average gut content
English Coast	Davison (1891)	Worm (*Arenicola*)	39,935–203,272 castings per acre per 24 hours
English Coast	Davison (1891)	Worm (*Arenicola*)	52,568–70,372 castings per acre per 24 hours
English Coast	Davison (1891)	Worm (*Arenicola*)	50,036–86,344 castings per acre per 24 hours
English Coast	Davison (1891)	Worm (*Arenicola*)	62,114–227,177 castings per acre per 24 hours
English Coast	Davison (1891)	Worm (*Arenicola*)	449–3,147 tons debris ingested per acre per year

TABLE 3. *Depth to Which Some Macro-Organisms Burrow in Bottom Sediments.*

Location	Authority	Organism	Depth
Pacific Island reefs	Gardiner (1931)	Worm (*Balanoglossus*)	several feet
The Wash	Kindle (1930)	Worm (*Branchiomima*)	5–6 inches minimum
Not stated	Macnair and Reid (1929)	Worm (*Arenicola*)	7–9 inches minimum
Northumberland Coast	Davison (1891)	Worm (*Arenicola*)	24 inches minimum
California Coast	Fenton and Fenton (1934)	*Phoronid*	4–6 inches minimum
New England Coast	Herrick (1893)	Lobster	few inches
California Coast	McGinitie (1935)	Ray (*Myliobatis*)	18 inches minimum
Formosa	Hayasaka (1935)	Crab	8 inches minimum

TABLE 4. *Faunal Density—Clyde Sea Muds.*
(Data from Moore, 1931)

Organism	Depth in Sediment (centimeters)							
	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8
Worms								
Nematodes (individuals per 100 sq. cm., 15.5 sq. in.)	398	658	457	269	89	40	16	0
Polychaetes (individuals per 100 sq. cm., 15.5 sq. in.)	22	9	15	6	3	2	0	0
Ostracods (individuals per 100 sq. cm., 15.5 sq. in.)	59	9	3	1	1	0	0	0
Copecods (individuals per 100 sq. cm., 15.5 sq. in.)	254	29	12	5	8	3	3	0

TABLE 5. *Statistical Comparison of Coral Lagoon Deposits.*

Location	Authority	Number of Samples	Average Md* mm.	Average QDΦ*	Average SKqΦ*
Bermuda	Todd (1939)	average of 15	.54	.660	.16
Florida Bays	Trask (1932)	average of 8	.040	2.16	−.15
Batabano, Cuba	Trask (1932)	average of 3	.019	1.91	.14
Bahamas	Trask (1932)	average of 1	.006	2.29	−.02
Bahamas	Vaughan (1918)	average of 4	.092	2.74	−.58
Andros Island	Vaughan (1918)	average of 4	.22	.52	−.104
Murray Island, Australia	Vaughan (1918)	average of 5	.79	.50	.168
Hermes and Pearl Reef, Hawaii	Thorp (1936)	average of 18	2.09	1.18	−.138
Pago-Pago Harbor, Samoa	Bramlette (1926)	average of 4	.031	1.51	−.129
Aua shoreline, Pago-Pago	Bramlette (1926)	average of 9	1.08	1.10	−.155
Great Barrier Reef, Australia	Trask (1932)	average of 1	.055	2.29	.82
Raiatea, Society Islands	Stark-Dapples	average of 48	.591	1.01	−.162

* Md represents the median diameter in millimeters.
QDΦ represents the phi-quartile deviation or one-half the spread in Wentworth units between the first and third quartiles.
SKqΦ represents the phi-quartile skewness. An SKqΦ equal to 1 indicates an interval of one Wentworth unit between the mean of the quartiles and the median.

SOLUTION OF ROCK BY ORGANISMS

Holothurians are known to dissolve rock as it passes through their bodies. Such is demonstrated by the change of pH of the fluid in the alimentary tract which may range from 4.75 to 7 before feeding and increases to 7 when the gut is filled with calcareous matter (Mayer, 1924b, p. 35).

Rock borers such as certain mollusks, algae, echinoderms, and worms are particularly effective in destroying large rock fragments (Agassiz, 1888, p. 288). Entire surfaces on coral reefs have been reported as consisting of small scalloped depressions made by sea urchins (Gardiner, 1931, p. 101). Vaillant (1891) estimates the annelid *Leucodore* may bore as many as 250,000 to 300,000 holes per sq. meter each approaching an inch in depth. Larger holes up to 14 mm. in diameter may be drilled by mollusks (Gardiner, 1931, pp. 106–109). Jehu (1918) reports of localities along the coast of England where the rock boring mollusk *Pholas* is locally lowering the chalk floor at rates ranging from .7 to 1.3 inches, and averaging .5 inches, annually. Rock borers appear particularly active in localities where certain agencies produce clean rock surfaces favorable for their attachment. Such agencies are strong wave and current action, heavy rain or strong influx of fresh water sufficient to periodically kill coral, and browsing animals such as gastropods, amphineura, and echinoids (Otter, 1930).

FORMATION OF TUBES AND BURROWS

Certain organisms, particularly worms, in the process of burrowing through sediments, construct vertical tubes. Such a worm is *Branchiomima*, which has been observed in large numbers in the deposits of the inter-tidal zone of The Wash, England (Kindle, 1930, p. 11). The tubes, 5 to 6 inches long, have walls which are partially cemented and project above the level of the ocean floor. As a result of this projection, they commonly act as a restraining influence upon shifting sediments, particularly where they are as numerous as hundreds per square yard. The enclosing sediments surrounding each tube have been bleached, apparently by the reducing action of the body juices. After the death of the organism, the burrows become filled with fine sediment and are preserved as small cylinders. Somewhat similar but longer openings dug by crabs in the beach deposits of Formosa have been reported by Hayasaka (1935). These tubes are associated with numerous pellets of faecal matter.

FAECAL PELLETS

Although partial cementation of sediments is initiated by tube forming worms, more is accomplished by organisms which cement detrital material into faecal pellets. Such faecal matter appears to be widely distributed over the floor of the ocean but is concentrated chiefly in shallow water. Thorp (1931) reports the presence of coprolitic material in one half of the samples of deep sea sediments collected from the floor of the Atlantic ocean off Panama. Buchanan (1890, p. 20) describes many pellets in the bottom sediments off the island of Arran in waters 90 fathoms deep and also at a depth of 50 fathoms of water near the mouth of the Congo. Buchanan (1890), Takahashi and Yagi (1929), Moore (1931), and Thorp (1931) have found that such pellets become glauconitized in deep water. Thorp also states that faecal pellets form the center about which phosphatic material accumulates, and Moore's (1931) analyses of pellets from the Clyde Sea muds contain as much as 30% P_2O_5.

Coprolitic pellets form a much more significant part of many marine sediments than might be suspected (table 6). In some instances the entire sedimentary material may be coprolitic (Moore, 1931). Generally, however, the identification of such material is somewhat difficult but recently Moore (1939) and Edge (1934) have demonstrated that certain organisms produce pellets of character-

istic shape. Damas (1935) states that along the Belgian coast a population density of *Cardium* of 1,000 per square meter will result in a yearly deposit of 45 centimeters thick or 1¼ million cubic meters of sediment per year over 250 hectares (617 acres). Such estimates of the amount deposited are probably excessive since the pellets do not constitute new material but are constantly passing through a cycle of being ingested again after their deposition. Hence, the figure indicating the thickness of sediment accumulated based upon the size and rate of discharge of pellets is undoubtedly not an exact measure of the rate of deposition.

TABLE 6. *Faecal Pellets in Sediments.*

Location	Authority	Organism	Quantity
Wilhelmshaven	Hantzschel (1939)	Worms, Pelecypods, Gastropods	Significant part of tidal flat sediments
Mouth of Congo	Buchanan (1890)	Worms	Large percentage of the muddy sediments
Atlantic-Panama	Thorp (1931)		Abundant in deep water sediments
Formosa	Hayasaka (1935)	Crab	Abundant on beach
Clyde Sea	Moore (1931)		40% of fine material
Belgian Coast	Damas (1935)	Mollusk (*Cardium*)	Adult deposits 420 pellets hourly; a population of 1000 per sq. meter will deposit a layer 45 cm. thick yearly
Raiatea, Society Islands	Stark-Dapples (1941)		Maximum of 1% of coral lagoon sediments

CONCLUSIONS

The writer's chief purpose has been to direct attention to the work of organisms in the preliminary stages of the diagenesis of sediments. Further information concerning the effect of such organisms upon sediments should furnish data on the environments of sedimentation, rates of deposition, quantity of expected organic content, and initiation of lithification. Even with the present limited knowledge concerning their quantitative importance, the following generalizations appear to be established:

(1) Material deposited in regions where benthonic animals are profuse is eaten and re-eaten many times before it is buried beneath a sufficiently heavy blanket of additional sedimentary debris to prevent further attack by organisms. During such journeys through the intestinal tracts of organisms there is a reduction in the diameter of the grain size and eventually the finest material may be either dissolved or carried away by current action. The reduction in particle size appears to be particularly true in some coral lagoons where most of the sediment on the lagoon floor is composed of particles of coarse and medium sand grain size. Lithification of such material would result in a lagoonal facies of rock which would be coarsely crystalline and massively bedded. Such a rock would present a sharp contrast with the fine-grained, thin-bedded strata which are considered lagoonal deposits.

(2) Where lamination is absent in rocks containing worm tubes recognized by a bleached zone surrounding the periphery of each tube, the bedding has probably been destroyed by burrowing organisms. If bedding can be observed under such conditions where burrowing forms are numerous, it has been observed that the rate of deposition of sediments exceeds the rate at which organisms may turn over the sediments. A case in point

is the tidal flat along the North Sea coast at Wilhelmshaven where Hantzschel (1939, p. 203) reports that re-working of the sediments by currents, and re-stratification proceed so rapidly that organisms have insufficient time to destroy the bedding. In describing conditions under which some black shales develop, Twenhofel (1939, p. 1185) states that the thin laminations and the excellent preservation of fossils indicates that neither a scavenger nor burrowing population is commonly present. Conversely, an absence of stratification was noted by Twenhofel and Broughton (1939, p. 251) and Twenhofel and McKelvey (1939, p. 109) in the bottom sediments of two Wisconsin lakes. Such destruction of laminae was caused by worm-like animals continuously reworking the deposits.

(3) Where the rate of sedimentation is slow, faecal matter tends to become cemented with glauconite, or its contained iron content may result in the formation of pyrite or limonite. Buchanan (1890, p. 21) states that near Ascension Island coprolitic mud could be observed to change gradually from a near-shore earthy variety to a glauconitized pelagic type. Similar observations have been reported by Takahashi and Yagi (1929) off the Japanese Islands. If deposition is rapid, the pellets are likely to be destroyed by the weight of the overlying debris, since when first deposited they are generally loosely cemented by mucoid material.

The relationship between benthonic organisms and the sediments on which they dwell should prove a fertile field for further research. From these studies should come additional criteria for the recognition of environments in which aqueous sediments were deposited, information concerning the removal or addition of organic matter to aqueous sediments, the environments in which fossil organisms lived and other facts which will serve to extend the boundaries of geological knowledge.

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CORRECTION

The paper by Dr. Gordon Rittenhouse in the August number of the *Journal of Sedimentary Petrology*, vol. 12, no. 2, pp. 85–89 on "Gravity versus Centrifuge Separation of Heavy Minerals from Sand" contains an error in that the figures for "Coefficient of Variation" were given in table 1, p. 86 instead of the figures for "standard error." The figures in this table should be .062, .043, .020, .017, .055, and .031. These figures should be written in order in the last line of the table for 4.7, 3.5, 5.9, 5.3, 5.6, and 3.4.

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FIG. 1, TABLE 1, DECEMBER, 1942

CHANGES PRODUCED BY MICROORGANISMS IN SEDIMENTS AFTER DEPOSITION*

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ABSTRACT

Significant numbers of bacteria have been found in recent sediments wherever critical tests have been made for their presence. Total numbers as well as the kinds of microorganisms decrease with core depth. Several physiological types of bacteria together with fewer yeasts, molds and actinomyces have been found, some at depths exceeding 15 feet. The demonstrated ability of the microorganisms to function in sedimentary materials in the laboratory under conditions simulating those in nature indicates that they could be active *in situ*, and changes in certain properties of sediments suggest that the microorganisms have been active.

Bacteria consume oxygen, and there are enough bacteria in sediments to account for the depletion of the dissolved oxygen. Similarly bacteria are probably responsible for the oxidation-reduction potential of sediments which ranges from Eh 0 to −0.5 volts whereas the overlying water is oxidizing in character. There are several ways in which the biochemical activities of microorganisms influence the hydrogen-ion concentration of sediments. Most types of organic matter are attacked by bacteria. The organic content and microorganisms influence the aggregation of particles. By altering the environmental conditions and by serving as a source of food, bacteria have a pronounced effect on the animal population of sediments.

It is still indeterminate if bacterial activity plays a role in the genesis of petroleum, but there are several ways in which it might. The changes in the calcium, iron, manganese, sulfur, phosphate and carbonate content of sediments attributable to microorganisms are mentioned.

INTRODUCTION

There are several lines of evidence which indicate that bacteria and allied microorganisms influence the diagenesis of sedimentary materials. (1) Significant numbers of living bacteria are found in recent sediments wherever critical tests have been made for their presence. (2) Several kinds of bacteria capable of altering various chemical substances or physico-chemical conditions occur in the sediments. (3) Controlled experiments in the laboratory show that the bacteria could be functional *in situ*, or in the environment in which they are found. (4) There is a correlation between the numbers and kinds of bacteria and the chemical and physico-chemical conditions found in the sediments.

BACTERIAL POPULATION

A few hundred to several million viable bacteria per gram of marine mud have been demonstrated by cultural procedures. The samples of mud have been collected and analyzed by methods which preclude the possibilities of extraneous contamination. Moreover, since there are far more bacteria in the mud than in the overlying water, and since the bacteria found in the mud are different from those found in other environments, there can be no question concerning the existence of bacteria in the mud.

In recent work, the coring instrument described by Emery and Dietz (1941) was used for the collection of mud samples for bacteriological analysis. The core barrel of the instrument (fig. 1) is lined with a long strip of 15-guage celluloid which facilitates the removal and examination of the mud core without unduly disrupting the natural stratification. With this instrument numerous cores ranging in length from 6 feet to a maximum length of nearly 17 feet have been taken from many types of sediments

* Contribution from the Scripps Institution of Oceanography, New Series No. 181.

from different depths of water down to 12,200 feet. In earlier work we have used a modified Ekman mud-sampling device, and the Trask coring tube has been used.

Radially central portions of the core samples have been dissected out aseptically and transferred to sterile tared

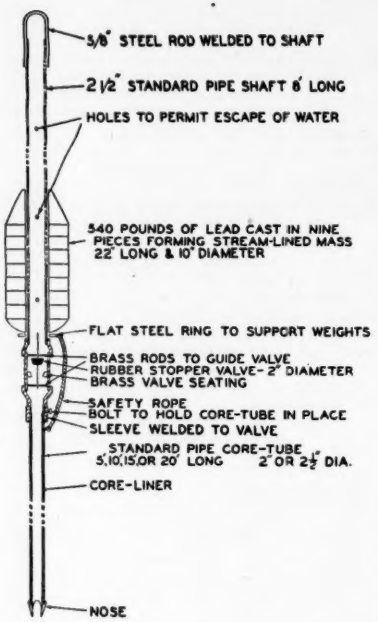
5/8" STEEL ROD WELDED TO SHAFT
2 1/2" STANDARD PIPE SHAFT 6' LONG
HOLES TO PERMIT ESCAPE OF WATER
540 POUNDS OF LEAD CAST IN NINE PIECES FORMING STREAM-LINED MASS 22" LONG & 10" DIAMETER
FLAT STEEL RING TO SUPPORT WEIGHTS
BRASS RODS TO GUIDE VALVE
RUBBER STOPPER VALVE- 2" DIAMETER
BRASS VALVE SEATING
SAFETY ROPE
BOLT TO HOLD CORE-TUBE IN PLACE
SLEEVE WELDED TO VALVE
STANDARD PIPE CORE-TUBE 5,10,15 OR 20' LONG 2" OR 2½" DIA.
CORE-LINER
NOSE

FIG. 1.—Coring device described by Emery and Dietz (1941).

bottles in which the weight of the samples could be ascertained. The samples were mixed and diluted with sterile sea water after which appropriate dilutions were planted on plates of nutrient sea water agar or in selective media designed to promote the growth of different physiological types of bacteria. The plate-count and minimum dilution procedures give information on the numbers and kinds of bacteria in the mud, and from the media pure cultures can be isolated for further study.

In nearly all cores examined the topmost portions, or the layer of mud in immediate contact with the overlying water, showed the largest bacterial populations. In the topmost 2-inch layer of mud carefully collected manually in shallow waters of Mission Bay, ZoBell and Feltham (1942) reported the presence of a maximum of 460,000,000 bacteria per gram of sedimentary material (dry basis). In different marine environments the number of bacteria in the surface layers of sediment ranges from thousands to hundreds of millions. Among the factors which influence the number of bacteria, the presence of available organic matter seems to be the most important (Henrici and McCoy, 1938, Williams and McCoy, 1935, Waksman et al., 1933, Waksman and Hotchkiss, 1938, ZoBell and Anderson, 1936). The particle size is also an important factor, there generally being far more bacteria in fine and colloidal sediments than in coarse ones (ZoBell, 1938).

With increasing core depth the bacterial population decreases sharply (Rittenberg, 1940). The decrease is most rapid in the first few inches after which it is comparatively slow. This is illustrated by the data in table 1 which shows the number of bacteria found at different depths of some cores from off the coast of Southern California. At depths exceeding 10 inches the decrease is gradual but more or less sporadic. In most cores fewer than ten thousand living bacteria per gram are found at depths below 10 inches, although occasionally a stratum of sediment containing millions of bacteria per gram is found at great depths. These bacteria-rich strata differ also in other characteristics which suggests that the bacteria are active *in situ*.

Bacteria do not contribute much to the mass of sediments, more than a billion cells being required to give a mass of one milligram. However, the bacteria may produce significant quantities of biocatalysts or enzymes which activate a large variety of chemical reactions in the sediments. Some of these enzymes may continue to be functional after the bac-

teria themselves are dead. According to Kreps (1934) organic catalysts or enzymes are concentrated in bottom deposits and the observations of ZoBell (1939) show that at least certain types of enzymes continue to be active in sediments in the absence of bacteria.

KINDS OF MICROORGANISMS

The majority of microorganisms recovered from sedimentary materials prove to be bacteria although actinomyces, yeasts, molds and algae have been noted. Sparrow (1937) has isolated 18 species representing 8 genera of saprophytic fungi from marine mud where they were found associated with decaying plankton. Blue-green algae and diatoms are commonly found on the bottoms of shallow lakes and seas but their activity is probably limited by the depth to which sunlight penetrates. Actinomyces (Umbreit and McCoy, 1941) appear to be fairly common in sedimentary materials.

The bacteria isolated from bottom deposits are biochemically versatile, being endowed with the ability to attack several inorganic substances and most kinds of organic matter. Bacteria are found in nearly all samples which reduce nitrate to nitrite, free nitrogen or ammonia. Rittenberg (1941) found *Vibrio desulfuricans*, an organism which reduces sulfate to hydrogen sulfide and possibly to free sulfur, in 44 per cent of the 450 samples of marine sediments from 160 localities and depths down to 16 feet below the sea floor. *Vibrio desulfuricans* appears to be active *in situ*, thereby influencing chemical and geological conditions.

Sediments from fresh-water lakes (Williams and McCoy, 1935) as well as marine sediments (ZoBell, 1938) contain an abundance of bacteria which decompose proteins with the formation of carbon dioxide, ammonium, hydrogen sulfide and a variety of intermediate products. Many kinds of carbohydrates are converted into carbon dioxide, carbon monoxide, methane and organic acids. Most lipins or fats which have been tested are hydrolyzed with the formation of fatty acids. The glycerol liberated when fats are hydrolyzed is oxidized by most bacteria and some of them utilize the fatty acids also. It is especially noteworthy that complex organic substances including chitin, spongin, waxes, hydrocarbons of varying degrees of complexity (Grant and ZoBell, 1942), cellulose, hemicellu-

TABLE 1. *Number of Bacteria Found per Gram of Wet Marine Sediments in Different Strata of Cores*

Core number Station location Water depth	XIV-37 32°26.4′N. 117°41.3′W. 3120 feet	XIV-45 32°36.4′N. 117°27.8′W. 3570 feet	XIV-53 33°03.3′N. 117°25.5′W. 1415 feet
Core depth in inches	Bacteria per gram	Bacteria per gram	Bacteria per gram
0–1	38,000,000	7,500,000	840,000
1–2	940,000	250,000	102,000
4–5	88,000	160,000	63,000
9–10	36,000	23,000	19,000
14–15	2,400	8,700	1,500
19–20	400	2,100	2,200
29–30	180	600	370
39–40	330	200	190
59–60	250	300	210
79–80	130	100	140
99–100	290	150	140

lose, agar (Bavendamm, 1931) and lignin (ZoBell and Stadler, 1940) are decomposed by certain mud-dwelling bacteria.

The aforementioned bacteria are heterotrophs requiring organic matter as a source of carbon or energy. Autotrophs, or those which obtain their energy from the oxidation of inorganic substances such as ferrous iron, manganous manganese, hydrogen sulfide, hydrogen, carbon monoxide, methane or ammonium as a source of energy, have likewise been found in recent sediments. If they are active *in situ* the autotrophs may be of importance in transforming inorganic substrates and in synthesizing organic matter (bacterial protoplasm) from carbon dioxide, water and minerals. It is doubtful, though, if the autotrophs are active except at the mud-water interface because most of them are aerobes whose activity requires free oxygen, and, as will be elaborated below, there is little or no free oxygen in sub-surface sediments.

EVIDENCE OF ACTIVITY

Merely finding microorganisms in sedimentary materials fails to prove that they are biochemically active in such an environment. Algae, diatoms, and other photosynthetic organisms sometimes found in sediments, obviously are not active below the zones penetrated by light. Similarly it is quite likely that many of the bacteria found in sediments are in a resting or inactive state. For example, the strict aerobes (the bacteria whose activity requires free oxygen) could not be active in the reduced sediments containing no oxygen from which they have been recovered. However, controlled laboratory experiments designed to simulate the marine environment as well as conditions found in the sediments indicate that many of the bacteria occurring in sedimentary materials are active *in situ*.

ZoBell (1934) has summarized the literature which shows that mud-dwelling bacteria multiply and are otherwise physiologically active at temperatures as low as any found on the sea floor (0 to −4° C.). They are not inhibited by the osmotic pressure of sea water nor by the high hydrostatic pressures encountered at great depth. Similarly, the bacteria thrive in an environment which is as oxidizing (Eh +0.08 volts) or as reducing (Eh −0.51 volts) as any which has been found in bottom deposits. Finally and most conclusive, the bacteria multiply and exhibit other manifestations of biochemical activity in samples of sedimentary materials from different depths and stations kept under observation in the laboratory.

OXYGEN UTILIZATION

When stored in the laboratory the bacterial population of freshly collected mud samples may increase from a ten- to a thousand-fold, the rate and magnitude of the increase being largely a function of the temperature. The storage is accompanied by changes in the organic matter content, pH, oxidation-reduction potential and hydrogen sulfide content. If the mud is mixed with sea water, dissolved oxygen is depleted from the latter. ZoBell (1939) has reported that muds from the Pacific Ocean consume from 0.5 to 3 cc. of oxygen per gram (dry basis), the exact amount being a function of the quantity and quality of organic matter present and the time and temperature of incubation. Anderson (1940) analyzed 131 samples of marine mud from the Cape Cod region and found that from 2.2 to 1000 cc. of oxygen was consumed by bacteria for each gram of organic carbon present; the organic carbon content of the muds ranging from 0.11 to 4.5 per cent of the sample.

Indications are that the rate of bacterial activity in marine sediments is very slow, particularly in deep water or at high latitudes where temperatures are low. The temperature range of approximately 80 per cent of the ocean floor is between 0 to 5°C. ZoBell (1940) has found that at this temperature marine bacteria consume an average of only 1.9×10^{-12} cc. of oxygen per cell per hour. At this rate it would require about ten million bacteria to utilize 1.0 cc. of oxygen in a year.

However, ten to a hundred million bacteria are often found in a gram of surface sedimentary material, which even at low temperatures is enough to account for the depletion of the dissolved oxygen from the interstitial water. In many localities the dissolved oxygen is consumed also from the immediately overlying water faster than it can be replaced by diffusion from above. In the shoal waters of Mission Bay, ZoBell and Feltham (1942) estimated that there were potentially enough bacteria in a square meter of mud to a depth of 1.0 cm. to consume from 6 to 18 cc. of oxygen per day. Actually they found that there was no free oxygen in the sub-surface layers of mud, and the oxygen tension of the overlying water was reduced.

Rarely is there the slightest trace of dissolved oxygen in the interstitial water of marine sedimentary materials. Therefore, it is believed that one of the first changes caused by bacterial activity is the depletion of oxygen, thereby rendering the environment anaerobic.

OXIDATION-REDUCTION POTENTIAL

After the oxygen is quantitatively consumed by bacteria, they continue to function at the expense of other hydrogen acceptors in the sedimentary materials as indicated by the reducing conditions, or low oxidation-reduction potential (Hewitt, 1936), created. This has been demonstrated in the laboratory as well as by measuring the oxidation-reduction potential of freshly collected sediments from different core depths. Several hundred electrometric determinations show that as a rule the oxidation-reduction potential of sediments decreases with core depth throughout the topmost 25 to 50 cm. from Eh 0, or slightly positive values, at the mud-water interface to Eh −0.4 volts. At greater depths the results have been erratic, although reducing conditions (Eh −0.2 to −0.5 volts) usually prevail. The overlying water is generally oxidizing in character (Allgeier et al., 1941).

The erratic results are attributed partly to technical difficulties in making the measurements and partly to the decrease in the content of reversibly oxidizable or reducible constituents at depths exceeding 25 to 50 cm. below the mud-water interface. The redox or poising capacity, as indicated by the amount of reducing substances in the sediments, usually decreases with core depth. This has been determined by noting the oxygen-absorbing capacity of samples. The redox capacity has also been determined from the amount of reducible dye such as methylene blue, for example, which is reduced by known quantities of mud.

The oxidation-reduction potential has a marked influence upon the direction, velocity and magnitude of chemical reactions which involve the exchange of electrons, or oxidation or reduction of reactants. Consequently, the oxidation-reduction potential would be expected to influence the diagenesis of sedimentary materials. Besides being related to the oxygen tension, Pearsall and Mortimer (1939) find that the state of iron, sulfur and certain nitrogen compounds is a function of the oxidation-reduction potential. According to Brujewicz (1937) the state of manganese, as well as iron, is a factor of the oxidation-reduction potential of marine sediments. Allgeier et al. (1941) find that the principal effect of the oxidation-reduction potential of freshwater lake deposits is on the content of ferrous iron, hydrogen sulfide and organic matter.

HYDROGEN-ION CONCENTRATION

Bacterial activity has the tendency to change the hydrogen-ion concentration or pH of sedimentary materials. Depending upon the numbers and kinds of microorganisms present, the substrate and environment conditions, they might increase the acidity or decrease it. The hydrogen-ion concentration is increased by the production of organic acids, including carbonic acid, from the decomposition of organic matter, by the formation of sulfate or nitrate, or by the utilization of ammonium. The hydrogen-ion con-

centration may be decreased by the reduction of sulfate or nitrate, by the utilization of organic acids, or by the formation of ammonium from nitrogenous compounds.

Bacteria capable of activating any one of the aforementioned reactions have been demonstrated in sedimentary materials. This, together with changes observed to occur under laboratory conditions, leads to the conclusion that bacteria are the principal dynamic agents which are responsible for changes in the hydrogen-ion concentration in sedimentary materials. The hydrogen-ion concentration of bottom deposits at depths to which carbon dioxide does not diffuse from the atmosphere is probably largely a function of the interrelated factors which influence the abundance, kinds and activity of bacteria. An appraisal of these factors will require much more quantitative information. According to Miyadi (1934), bacterial activity has a pronounced effect upon the hydrogen-ion concentration of lake mud, and Kusnetzow (1935) reports that bacterial activity may affect the hydrogen-ion concentration as well as the oxidation-reduction potential of an entire water basin.

Besides influencing the solubility and reactivity of certain constituents of sediments, the hydrogen-ion concentration also influences the oxidation-reduction potential. Its effects on base exchange and on the properties of clay have been discussed by Kelley (1939) and Grim (1939).

The hydrogen-ion concentration of the topmost layers of bottom deposits is usually nearly the same as that of the overlying water. For sea water it ranges from pH 7.6 to 8.3, depending primarily upon the depth of the overlying water and its origin. In some cores from the Gulf of California and the Channel Island region off the coast of Southern California the pH increases with core depth to as much as pH 8.9, and in other cores it decreases with depth to as low as pH 7.2. In freshwater lakes the range is far greater (Allgeier et al., 1941), varying considerably from lake to lake.

The unpublished observations of Rittenberg and Revelle at the Scripps Institution of Oceanography indicate that the pH of marine sediments is more related to particle size than to core depth. The highest pH values which are found usually occur in sediments in which most of the sulfate in the interstitial water has been reduced, presumably by bacterial activity. *Vibrio desulfuricans*, an anaerobic bacterium which reduces sulfate, has been found to be quite widely distributed in these sediments.

ORGANIC MATTER

An appreciable portion of the organic content of recent deposits may consist of fragments of various sizes of the bodies of animals and plants (Twenhofel, 1939). While some of this may be buried and preserved more or less intact in the sediments, the remains of most organisms are rapidly disintegrated by bacterial activity.

The majority, if not all, of the bacteria occurring in sediments require organic matter for building material and energy. The gradual decrease with core depth of the organic content of bottom sediments gives further evidence that bacteria have been active since their deposition. In general, the changes in the quality as well as in the quantity of organic matter in samples of sedimentary materials with core depth are greatest where bacteria are most abundant, namely, in the topmost few inches of mud (Trask, 1932).

The total quantity of organic matter decreases 10 to 20 per cent in the first two or three inches, and a like amount in the next 2 or 3 feet. At core depths exceeding 2 or 3 feet changes in the organic content of sediments is almost imperceptible as a rule. The work of Anderson (1940) shows that the organic matter becomes more refractory to bacterial oxidation with core depth, probably because the most oxidizable fractions are oxidized first leaving the so-

called humus (Waksman, 1933). It is estimated that between 30 and 40 per cent of the organic matter which is utilized by bacteria is converted into bacterial protoplasm which is fairly complex. Possibly a large percentage of the humus and other residual organic matter in older sedimentary material consists of bacterial cells or the remains thereof.

If it is permissible to generalize in terms of what our fragmentary observations indicate are mean conditions, it can be pointed out that in sediments taken from depths exceeding 2 or 3 feet, the order of magnitude of the bacterial population is thousands per gram. Throughout a foot of sediments from this depth the organic content has been found to decrease approximately 1.0 mgm. per gram of sediment. Assuming that uniformitarianism has prevailed and that the bacteria utilize organic matter at the rate of 10×10^{-12} mgm. per cell per hour (an approximation based upon laboratory observations), it would require around 10,000 years for the bacteria in one gram of such mud to oxidize 1.0 mgm. of organic matter. According to Trask (1939) sediments from this region have been deposited at the rate of around one foot in 10,000 years. While allowances must be made for errors in arriving at these estimates, it is significant that the order of magnitude of the estimates made by the bacteriologists approximate those made by the geologists.

BINDING ACTION

Besides influencing the texture and composition of sedimentary materials, the organic content and especially bacterial cells have a tendency to cement particles together thereby influencing the lithification of sediments (Shrikhande, 1936, and Peele, 1940). Many bacteria are extremely adhesive, growing tenaciously attached to solid surfaces, and some of them produce mucilaginous exudates. Filamentous cells also have a binding action on the aggregation of particles. Martin and Waksman (1940) report that microorganisms have a marked binding action on soil particles, the extent of the binding depending primarily upon the types of organisms and the quality of the organic matter present. While there may not be enough living cells to have any appreciable binding effect, there are probably thousands of times as many dead and partly decomposed bacterial cells as the number of living cells which can be demonstrated.

EFFECT ON OTHER ORGANISMS

As pointed out by Twenhofel (1939) most sediments after deposition contain plant and animal matter which serves as a source of food for numerous mud-eating, burrowing and browsing animals. Such animals have far-reaching effects on the diagenesis of sedimentary materials, and in turn bacteria influence the distribution and activity of such animals. By depleting the dissolved oxygen content, by reducing the oxidation-reduction potential, by producing hydrogen sulfide and other toxic products, and by increasing the hydrogen-ion concentration, bacteria create environmental conditions in certain localities which are inimical to other forms of life. No burrowing animals are found in black stinking muds from which bacteria have consumed all of the oxygen and produced large quantities of hydrogen sulfide.

On the other hand bacteria may be beneficial by serving as an important source of food for mud-dwelling animals and by mineralizing organic matter with the production of plant nutrients. It has been demonstrated by Baier (1935), MacGinitie (1935) and ZoBell and Feltham (1938) that many mud-dwelling animals are nourished largely by bacteria which they ingest and digest. The bacteria assimilate dissolved organic matter as well as lignin, spongin, chitin, cellulose and other complex compounds which are unfit as food for most types of animals which can utilize the bacteria.

The bacterial flora of a marine mud flat as an ecological factor has been stud-

ied by ZoBell and Feltham (1942). They conclude that the numbers and kinds of mud-burrowing animals as well as the depths to which the animals penetrate are influenced by environmental conditions produced by bacteria and allied microorganisms.

PETROLEUM GENESIS

It is still indeterminate if bacterial activity plays a direct role in the formation of petroleum but the accumulating evidence is highly suggestive. In the transformation of organic matter, bacteria convert it into substances which are more petroleum-like by reducing its nitrogen, oxygen, phosphorus and sulfur content (see analyses summarized by ZoBell, 1942). The low oxidation-reduction potentials which bacteria create in certain environments are conducive theoretically to the formation and accumulation of hydrocarbons. Lipolytic bacteria which hydrolyze fats with the liberation of fatty acids occur in sediments. It would be necessary only to remove two atoms of oxygen from these fatty acids to give fairly long-chain hydrocarbons, but to date bacteria which do this have not been found. Methane-producing bacteria are widely distributed in sedimentary materials but bacteria which produce higher hydrocarbons, with the exception of complex polyene pigments and their allies (Fox and Anderson 1941), have not been demonstrated.

The unconfirmed report of Ginzburg-Karagicheva (1936) finding 93 different saturated and unsaturated hydrocarbons besides methane being produced by anaerobic bacteria and that of Sturm and Orlova (1937) of a liquid hydrocarbon fuel being produced anaerobically from fats cannot be ignored.

On the other hand, the work of Bushnell and Haas (1941), Grant and ZoBell (1942) and others shows that benzene, cyclohexane, toluene, xylene, naphthalene and several aliphatic hydrocarbons from methane up to paraffin and waxes are oxidized by certain bacteria. Is it possible that such bacteria destroy hydrocarbons as rapidly as they are produced in sedimentary materials except in certain source beds where conditions are not conducive to the activity of hydrocarbon-oxidizing bacteria? The answer to this question may have a bearing upon the explanation of petroleum formation and accumulation.

One popular theory which has been advanced to account for the origin of oil premises the presence of free hydrogen in the source beds. It is possible that the hydrogen could be produced by bacterial activity. Bacteria which produce hydrogen during the anaerobic decomposition of organic matter occur in bottom deposits at all depths which have been explored. Allgeier et al. (1932) noted that after prolonged incubation under anaerobic conditions up to 12 per cent of the organic content of lacustrine sediments was converted into gaseous products consisting of 65 to 85 per cent methane, 3 to 30 per cent carbon dioxide, 3 to 22 per cent nitrogen and 1 to 3 per cent hydrogen. We demonstrated appreciable quantities of hydrogen as well as methane in freshly collected sediments from the Gulf of California.

INORGANIC CONSTITUENTS

Many workers attribute the origin of sedimentary iron formations primarily to the activities of microorganisms. The direct and indirect ways in which bacteria influence the solution or precipitation of iron in sediments have been outlined by Starkey and Halvorson (1927) and Baier (1938). They also discuss the ways in which compounds of manganese are transformed by biological agencies.

Thiel (1928) points out that bacteria are agents of rock decomposition. When bacteria are present in percolating water 50 per cent more mineral matter may be dissolved from igneous and sedimentary rocks than when bacteria are absent. Aluminum is liberated from hydrous aluminum silicates during rock decay by bacterial action. Potassium is leached from potassium bearing minerals due to its assimilation by bacteria and fungi.

Zinc blend is oxidized to zinc sulfate, and zinc carbonate and silicates are dissolved by the sulfuric acid formed by the bacterial oxidation of hydrogen sulfide and sulfur. There are numerous ways in which sulfur compounds are transformed by bacterial activity. Thiel (1930) reports that calcium phosphate as well as calcium carbonate is dissolved by bacteria which produce acid during the decomposition of organic matter.

If bacterial activity has any effect on the precipitation or subsequent dissolution of calcium carbonate, it is caused primarily by changes in the pH or hydrogen-ion concentration of the sediments or of the overlying water. In general, high pH values promote the precipitation of calcium carbonate while low pH values favor the dissolution of calcium carbonate.

The role of microorganisms in the precipitation of calcium carbonate has been summarized by Bavendamm (1932) and Baier (1937). According to Baier bacteria effect calcium carbonate precipitation primarily by their effect on the pH and secondarily by their effect on the carbon dioxide tension and organic matter content of sedimentary materials. To these could be added the indirect effect that bacterial activity may have on environmental conditions which influence other biological entities such as animals with calcareous remains and photo-synthetic organisms which are known to influence the availability and solubility of calcium.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 3, P. 137, DECEMBER, 1942

PROFESSOR CHARLES SCHUCHERT

Friday, November 20, 1942 saw the passing of Professor Charles Schuchert, emeritus professor of geology and paleontology in Yale University.

His passing leaves a vacant place in the hearts of many American geologists and paleontologists who were his firm friends. Professor Schuchert was born of German parentage in Cincinnati, Ohio on July 3, 1858, and his age at the time of his death was past 84 years. He is remarkable among American geologists in many respects. He had no high school education; no college training other than as might have been acquired from contacts with learned men. He held no degree except honorary ones; he was essentially a self-made man. As a boy and a young man, he became interested in the fossils which were so abundantly present and excellently preserved in the rocks forming the hills about the city of Cincinnati. He devoted his spare time to collecting these fossils. Collecting fossils was his chief interest in those days, and it continued to be one of the chief sources of his pleasure until the last years of his life. The brachiopods among these fossils were perhaps those most beautifully preserved and through his own collecting and exchanges with others living in other countries, he acquired a very large and varied collection of brachiopods. Ultimately, he and his collection attracted the attention of James Hall and the young collector was employed by this eminent paleontologist to assist him in his studies. Later he was assistant to C. E. Beecher and finally he became curator of geology in the U. S. National Museum. Following the death of Beecher, Professor Schuchert was called to Yale in 1904 where he remained until his retirement in 1923. Hard work, diligence, and loyalty to his chosen science advanced him to the positions of honor and responsibility which he has held.

He early became convinced that by means of fossils one should be able to dilineate the boundaries of the lands and seas of the past. He collected data bearing upon this problem and the work finally culminated in his magnificent contribution on the paleogeography of the past.

As a professor in Yale University, he was deeply attached to all of his graduate students who showed their loyalty to him in the quality of their work, and the times have been many when he used his own funds to give a student the opportunity to do field or laboratory work which could yield no returns to him other than the gratitude of the student. This work, in many cases, had no other objective as far as he was concerned than to give assistance to students in need. The work was merely a way of helping without injury to a student's pride.

The writer owes more to Professor Schuchert than to any persons other than his mother and his wife. He was very close to him during three years of graduate study, and he maintained a close connection by correspondence for 32 years. His doctorate thesis was written under Professor Schuchert's guidance, his first scientific paper was in collaboration with him, and he did field work with him in the summer of 1910 in Labrador and Newfoundland. Professor Schuchert was always kindly, always helpful. During these years, he became involved in controversies with some of his contemporaries and relationships with some of his earlier friends were brought to a close. The writer does not remember Professor Schuchert's ever expressing bitterness over such breaking of relationships, or his making a derogatory remark concerning those who had been his friends. His feelings with respect to these former friends were concealed.

A great man, a good man, a great scientist, a great investigator has gone. His going will be deeply mourned by those who have worked with him and who had learned to love him.

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REVIEWS

A Symposium on Hydrobiology. Madison, Wisconsin. University of Wisconsin Press, 1941, pp. ix + 405. Price $3.50.

In this handsome volume are published the proceedings of an Institute of Hydrobiology held at the University of Wisconsin, September 4–6, 1940. Although the editors, by publishing testimonial material separately, have been careful to avoid the appearance of a festschrift, the immediate occasion of the conference was the eighty-ninth birthday of President Emeritus Edward A Birge. The volume presents a fairly balanced purview of the modern field of hydrobiology, and thus a thoroughgoing tribute to Dr. Birge's leadership.

Thirty-two invitation papers appear in full, and in addition 16 contributions to a volunteer program are represented in abstract. The great interest in the economic aspects of hydrobiology is fully recognized, in that approximately half of the longer articles deal with these; to analyze the table of contents on this basis is rather misleading, however, since the term economic covers such diverse and important fields as sewage disposal, water supply and swimming pool sanitation, malaria control, and schistosome dermatitis, as well as the management of game and food fisheries. Two outstanding contributions to the last-mentioned problem are included, those of Thompson and of Swingle and Smith; since it has been possible to measure the total fish production and annual yield directly, by poisoning in Illinois, by use of experimental ponds in Alabama, one feels that "at last we are getting somewhere."

The more purely limnological half of the program makes obeisance to history through Needham's anecdotal *Fragments of the History of Hydrobiology;* to geography, through Sears' stimulating *Human Culture Forms as Influenced by Lakes;* and to sociology, through Wehrwein's extremely interesting *The Economic Phases of Riparian Land Use.* New information is brought to bear on old problems in Utterback's discussion of penetration and scattering of light, in Burr's excellent summary of the limnological research on photosynthesis, and in Hubbs' challenging account of speciation in fishes. Weston pleads eloquently for limnological recognition of the aquatic fungi, and Umbreit and McCoy, in a paper of great importance to students of lake sediments, indicate that Actinomycetes of the genus Micromonospora are the essential limnetic transformers of resistant organic materials. Probably the most distinguished essay, however, is that of Waksman on *Aquatic Bacteria in Relation to the Cycle of Organic Matter in Lakes,* which is especially valuable for its résumé of recent Russian literature. Of unusual interest also is Renn's demonstration that Anopheles larvae, by a nearly unique feeding mechanism, can utilize the particulate matter concentrated in the air-water interface, provided the surface tension is not lowered by the usual components of culture media.

A symposium inevitably suffers from lack of unity, and in this case, when the editors have been so comprehensive in their scope and so generous in arranging for many individually excellent articles, it is perhaps ungracious to complain that the contributions are uneven in quality, and that some subjects are neglected. It appears, nevertheless, that more attention might have been devoted to lake sediments; Twenhofel's contribution was published in full elsewhere, and Happ's summary of the sediments of reservoirs, while very-valuable, is of too limited a nature properly to represent the subject in a collection of this sort. Other topics remarkable for their omission are lake currents, biogeography, and the productivity of plankton, while the almost complete neglect of marine hydrobiology will be disappointing to oceanographers. But these minor criticisms do not affect the reviewer's opinion that the editors are to

be congratulated on a well-planned and well-executed presentation of modern problems in hydrobiology. The published version will be equally prized by those who were fortunate enough to be able to attend the symposium and by those who were not. The volume is beautifully printed and is free from textual errors, but it lacks an index.

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The Pre-Quaternary Rocks of Sweden, VI, Reef Limestones, by ASSAR HADDING, pp. 137, 88 text figures, Meddelanden från Lunds Geologisk-Mineralogiska Institution, Lunds Universitets Årsskrift, N. F., Avd. 2, bd. 37, nr. 10, 1941.

This work is the sixth of a series of papers on the sedimentary rocks of Sweden, which have been published by Hadding. Those previously published are: I. A Survey of the Pre-Quaternary rocks of Sweden, 1923; II. The Paleozoic and Mesozoic Conglomerates of Sweden, 1927; III, The Paleozoic and Mesozoic Sandstones of Sweden, 1929; IV. Glauconite and Glauconitic Rocks, 1932; and V. On the Organic Remains of the Limestones, 1933. Each of these works is of interest to sedimentationists and of much importance to geologists in general. Each represents work on a rarely attempted task, namely; a complete description and interpretation of a single kind of rock for an entire country.

The reef limestones of Sweden are in three divisions of the geologic column, and they occur in three different parts of Sweden. The most important reefs are in the famous Silurian section which composes the Island of Gotland in the Baltic Sea. The other two occurrences are in the region of Dalecarlia, in north central Sweden, and in Scania, in southern Sweden. Most of the book is devoted to a description of the reefs of Gotland; about two-thirds of the pages relate to these reefs. The reefs of the Ordovician-Silurian section of Dalecarlia are considered in 21 pages, and 10 pages treat of the Cretaceous (Danian) reefs of Scania. There are five pages of bibliography and an index of five pages.

The reefs of Gotland are considered from the points of view of vertical and horizontal distribution, their forms and dimensions, origin, composition of organic materials, and other angles. As the reefs are known only from outcrops of the containing formations (stages), the complete distribution remains to be learned. The great cliffs on the west side of Gotland, known as klints, give some of the best exposures and several of these are figured in the text. The forms and dimensions of the reefs are given in some detail and it is pointed out that the typical form of a reef is that of an inverted cone, and that all reefs which could be completely observed have such forms. The cones do not have regular contacts with the enclosing sedimentary rocks, but are indented by them and parts of the reefs project into them. Some reefs have been formed by union of two smaller ones. The basal or apical angles of the reefs range from acute to obtuse, and those with extremely obtuse angles are essentially lens-shaped. The thicknesses of the reefs, that is, the heights of the cones, range from 1 to 20 meters. Widths and lengths, or the horizontal dimensions, range from a few to several hundred meters.

The reefs have a skeletal structure of calcium carbonate of organic origin and a matrix which fills the interstices in the skeletons. The reef-forming organisms in order of importance are stromatoporoids, corals, bryozoans, and calcareous algae. The stromatoporoids are by far the most abundant and most important. They are several times as abundant as all other reef-building organisms combined. The reef-building corals are members of the Tabulata, Heliolitidae, and some of the colonial Tetracoralla. Bryozoans assist locally, but are not generally abundant as reef builders. Calcareous algae are not particularly common. On the other hand, Hadding states that it was often found

that calcareous algae and bryozoans contributed to a reef body to a higher degree than the corals. Non-reef building organisms are sporadically present in different parts of every reef.

The matrix of the reefs in some places consists almost exclusively of fine calcareous mud with scattered small fossils. In other places it is composed of coarse fragments which were obviously derived from the reefs themselves. In places the matrix is rich in grayish-green clay-mud. Most reefs underwent recrystallization after deposition.

Relations of the reefs to the bordering stratified rocks range from indistinct to very distinct. The contact between the reefs of these bordering rocks is irregular, and, in some cases, extremely so. The rocks bordering many reefs are well stratified crinoidal limestones.

Hadding is of the opinion that the tops of the reefs were not more than a few meters above the surrounding bottoms where the bordering sediments were deposited. This is stated to be shown by the inverted cone shapes of the reefs which would not have been able to maintain upright positions unless supported by the surrounding sediments, and by the fact that the reefs built directly over these sediments when they expanded. The two sides of the reefs have different bordering sediments.

The reefs are considered to have been built at depths estimated to range from 5 to 50 meters and the reef-building organisms are assumed to have been killed either by being smothered because of deposition of muds over them, or by elevation of the bottoms above sea level for a short time. Elimination must always be considered to have been brought about by the appearance of conditions unfavorable for the growth of the reef building organisms. Hadding concludes that all "reefs were formed at slight depths, below the level for the formation of pure littoral sediments, such as conglomerates, sandstones, oolites, and coarse fragment limestones, but above the level for deposition of the thin-bedded mudstones formed in open water" (p. 72). Where calcareous algae are absent, it is inferred that these reefs were built at depths too great for these organisms.

The structure of the reefs commonly is massive without any bedding except as such may be indicated by the plastering of the reef building organisms over each other. The reefs contain good bedding in places due to the deposition of ordinary sediments; in other places the structure is conglomeratic due to the rolling together of spherical colonies of stromatoporoids and corals, and in other places the structure was determined by the accumulation of loose fragments and fine detritus from the reefs.

The review of the literature pertaining to the Gotland reefs is given on the last 16 pages (pp. 79–94).

The reefs of the Dalecarlia region are in the Leptaena limestone (Leptaenakalk) of high Ordovician age. The reefs range from nodules to lenticular bodies up to 1000 meters in horizontal extension and a thickness up to 30 meters. Calcareous algae seem to be responsible for these reefs and other organisms have scattered occurrences. Some of the algae are encrusting and others are branching. The reef materials have been recrystallized. Many of the reef bodies have been quarried.

The Danian (Cretaceous) reefs are in southwestern Scania (southern Sweden). The reefs have been seen only in a single quarry, and the true extent is not known as the surface is generally covered with glacial deposits. The reefs are in the form of nodular lumps and extended lenses. The shapes are those of inverted obtuse cones. Most have diameters in the range of 20 to 50 meters, and they generally range up to about 10 meters in height, but one measured was found to be 1000 meters long, 500 meters wide, and about 40 meters high. The reef building organisms are mainly corals among which the branched Hexacoralla are the most important. Other organisms, as bryozoans and crinoids, are common. Reef fragments and calcareous muds fill interstices within the reefs. Recrystallization has taken place in all the reefs.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 12, NO. 3, PP. 141–142, DECEMBER, 1942

JOURNAL OF SEDIMENTARY PETROLOGY STYLE SHEET

To assist authors in the preparation of manuscripts for the *Journal of Sedimentary Petrology*, the following list of suggestions has been prepared.

REFERENCES

References should be checked and rechecked before a manuscript is submitted to the editor. Extreme care should be taken so that each reference, especially each foreign reference is correctly abbreviated. Often times, abbreviations are so abbreviated as to make checking difficult for readers, particularly foreign readers. Authorities should not be referred to by number. For example, do not write: "The formation has been assigned to the Silurian (7). Write instead: The formation has been assigned to the Silurian (Brown 1895, p. 32).

In listing references, follow the style now used by the *Journal of Sedimentary Petrology* which is as follows: Authors names are capitalized, followed by the date of publication in italics (not parentheses), the title of the article, followed with a colon and the title of the reference in italics. Authors should be listed alphabetically.

SMITH, J. B., *1934*, The authigenic minerals of the Brown formation: *Jour. Sed. Pet.*, vol. 4, pp. 12–22.

If two works by the same author are used, the author's name in the second reference should be represented with a dash.

PREPARATION OF MANUSCRIPT

No article appears in the *Journal of Sedimentary Petrology* without an abstract. Acknowledgments should be given toward the close of the introduction. Conclusions, if listed, or summary, appear at the end of the manuscript.

Manuscripts should be double-spaced, clearly typewritten and submitted on firm, white paper. Articles should not be submitted on onion skin paper.

The material in the manuscript should be well organized so that the reader can easily understand what the author has to say without added effort. Spelling, sentence structure, and logical sequential arrangement are three of the most important factors in writing a good article.

WORD USAGE

Manuscripts should be written as concisely as possible, using only those words necessary for easy reading and clear-cut meaning. Wordy manuscripts are difficult to read, difficult to edit and unnecessarily expensive to publish. Long, involved sentences make reading difficult and a long sentence may express the opposite of what is meant.

Following are a few word suggestions for authors:

Amount when *quantity* is a better word.

Above, referring to material stated earlier in the manuscript, is not good form.

Latter cannot be used properly in referring to items in a series of more than two.

Percentage is singular.

Some is often used when not needed as "some data."

Very, *much*, *more* are used too often.

Avoid overuse of *therefore*, *however*, *more* or *less*, *thus*, etc.

TITLE OF PAPER

Titles should be brief, explanatory and interesting. Authors should attempt to avoid such words as "Notes on," "The," "A," "On the," "Suggestions regarding," "Some facts on," "Relations between." Such titles are unnecessarily wordy and irritating to the librarian and bibliographer.

General headings should also be brief. They should be centered in the manuscript and capitalized. Their main purpose is to inform the reader of the contents of the paper and to facilitate reading.

Subheadings, starting a paragraph, should be italicized and followed with a period and a dash.

GENERAL INSTRUCTIONS

The first page of the manuscript should be headed with the title of the paper, the author's name, his address and the ab-

stract. Each successive page should have the author's name on the upper left hand corner and the page number on the upper right hand corner.

The author should indicate on the margin throughout the manuscript where a figure, table, or photograph is to be inserted.

Legends for pictures, line drawings or figures should not be typed in the illustration or manuscript. They should be attached to the illustrations.

Present practice in the *Journal of Sedimentary Petrology* with respect to illustration preference is as follows:

The words "figure" and "table" are not capitalized or abbreviated when used as part of the manuscript text.

> "The former and present courses of the tributary stream are shown on the map of figure 2."

Abbreviate "figure" when it is used for a reference.

> "The shores of Monrovia consist of frontal and interlobate deposits which are predominantly outwash material (fig. 2).

Table is not abbreviated.

Capitalize and abbreviate "figure" and capitalize "table" when used as part of the legend of an illustration:

> "Fig. 9.—Diagram showing first quartile distribution of the sediments of Monrovia."

Hyphenated words and punctuation should be carefully and correctly used. Numbers under 10 are written out except when used as a unit of measurement. Long quotations should be set apart from the text in the manuscript so that they they can be easily indicated for the printer as long quotations are set in small type.

Footnotes should be used as seldom as possible and only when absolutely necessary.

PHOTOGRAPHS AND LINE DRAWINGS

Illustrative material to accompany research articles usually falls into one of two categories: (1) photographs; and (2) line drawings. If photographs or line drawings are considered important enough to be published as part of the article, as much care should go into their making as in the writing of the article itself.

Some authors prefer line drawings to photographs. Both are acceptable to the *Journal of Sedimentary Petrology*. Line drawings, according to the editor, may contain a personal equation, but they may also emphasize the more important features.

With respect to photographs, the author should keep in mind that the best results are obtained in reproducing them if the pictures are submitted as "glossy prints." So-called "matte" or dull-surfaced photographs tend to make fuzzy and indistinct printed reproductions. Glossy contact prints make the best reproductions and, with reasonable care, even enlargements of several diameters give good results. In short, *follow the rules for making the best quality prints to be sure that photographs will reproduce well.*

Line drawings should be planned for reproduction on a small scale as large figures are difficult to handle by the printer. Be sure that they are submitted in black and white. Drawings of any sort with portions done in colors do not reproduce well. Lines should not be so fine that they are "lost" in reproduction for often such material must be reduced and in the process fine lines lose their identity.

Drawings ought to be submitted of such a size that the least possible reduction will have to be made. Scale of reproduction preferred by the author should be indicated on the line drawings or figures. In preparing the illustration (lettering, symbols, etc.) the scale of reproduction should be kept in mind. Be as careful and as neat as possible.

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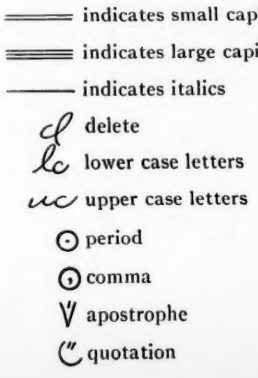

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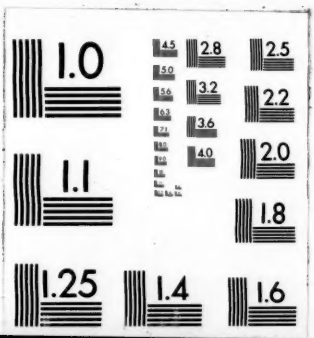
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